NGT-21-002-080
NGT-80001

NEPTUNE

N *UCLEAR*

E *LECTRIC*

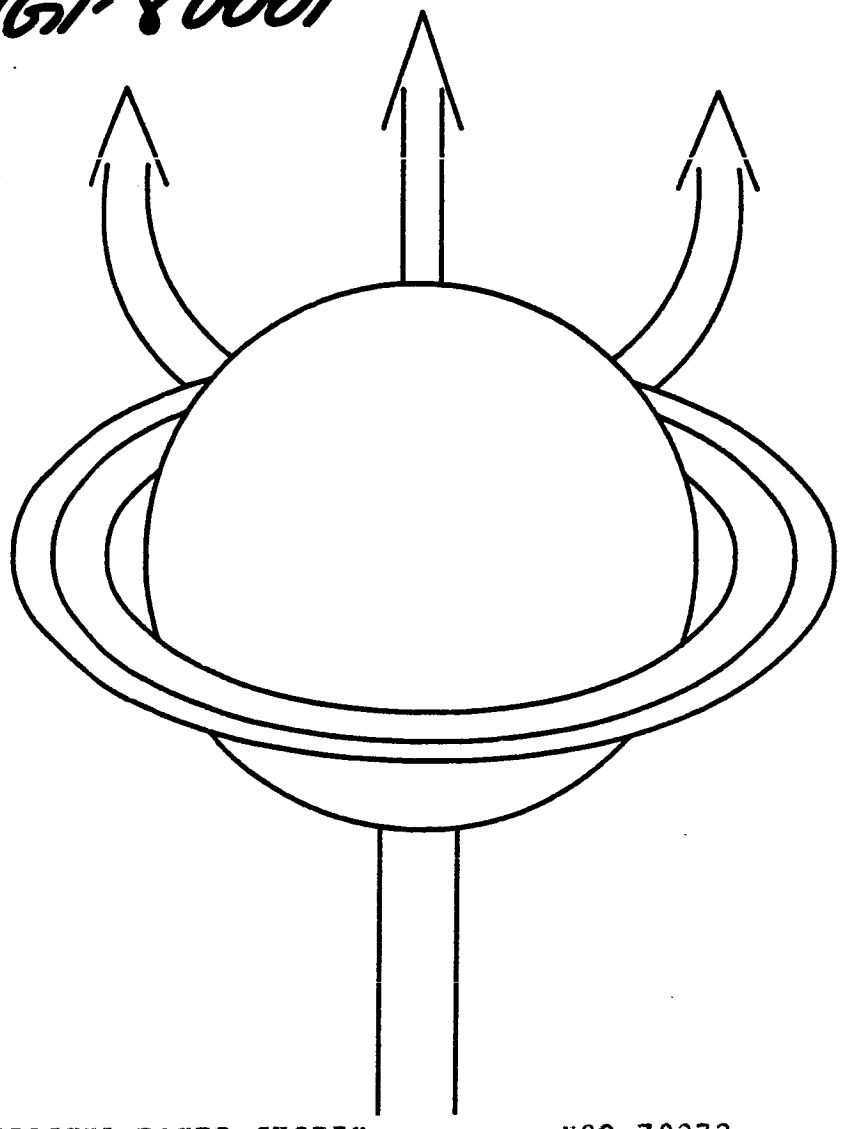
P *ROPULSION*

T *URBINE DRIVEN*

U *RANIUM*

N *ITRIDE*

E *NERGY SOURCE*



DAVID SENOR CARL BEARD
STEVE HAYES DARRYL ARCHER
MICHAEL GRAVES

TEXAS A+M UNIV.,
COLLEGE STATION

UNIVERSITIES SPACE RESEARCH ASSOCIATION

NASA/USRA University Advanced Design Programs

Onyx One Building • 17225 El Camino Real • Suite 450 • Houston, TX 77058 • (713) 480-5939

February 8, 1989

NASA Scientific and Information Facility
800 Elkridge Landing Road
Linthicum, MD 21090

Attention: Accessioning Department

Dear Sirs:

Per instructions from C.W. Hargrave, transmitted with this letter are 6 boxes of final university reports (2 copies each) to be incorporated into the STAR system. The NASA/USRA University Advanced Design Program operates under grants from NASA Headquarters (NGT-21-002-080 and NGT-80001). Additional reports will be similarly transmitted in bulk as they are received by our office.

Sincerely,

Greg R. Smith

The NEPTUNE Power System

A boiling potassium space nuclear power/propulsion reactor system

by

Darryl Archer
Carl Beard
Mike Graves
Steven Hayes
David Senor

ABSTRACT

The Nuclear Electric Propulsion Turbine-driven Uranium Nitride-fueled Energy source consists of a boiling potassium space reactor system providing electrical power for habitation and propulsion. The system is designed for a 20 year life to accommodate a manned, return mission to the outer planets. Primary emphasis of the design is placed on the reactor and propulsion systems in order to provide a framework for a future mission of this type. The selection of the reactor system and propulsion components was based on the power requirements for the propulsion due to the fact that it represents the bulk of the power consumption. The entire system is designed to meet the mission lifetime requirements with a high degree of reliability. The work presented is a baseline design capable of fulfilling the mission requirements. Recommendations are made throughout for possible future work to further detail the system.

TABLE OF CONTENTS

	Page
Chapter One: Introduction	1
Chapter Two: Power Requirements	6
Chapter Three: Core Design	11
Chapter Four: System Analysis	39
Chapter Five: Propulsion	53
Chapter Six: Shielding	60
Chapter Seven: Design Summary	73
Appendix One: Code Listings	78

LIST OF FIGURES

CHAPTER ONE:

Figure 1-1. Spacecraft Schematic
Figure 1-2. NEPTUNE System Schematic

CHAPTER TWO:

Figure 2-1. Dimensions of Single Module
Figure 2-2. Module Configuration for Mission

CHAPTER THREE:

Figure 3-1. Two Core Configuration
Figure 3-2. Coolant Orificing Scheme
Figure 3-3. Pressure Tube and Control Blade Arrangement
Figure 3-4. Reactor Cross Section
Figure 3-5. Flux Distribution as a Function of Energy Group
Figure 3-6. Radial Flux Profile
Figure 3-7. Axial Flux Profile
Figure 3-8. Critical Heat Flux as a Function of Quality
Figure 3-9. Axial Power Profile
Figure 3-10. Radial Power Profile
Figure 3-11. Fuel Pin Temperature Distribution
Figure 3-12. Nusselt Number as a Function of Quality
Figure 3-13. Unrestrained UN Fuel Swelling as a Function of Burnup
Figure 3-14. Fuel Pin Cross Section
Figure 3-15. Vertical Fuel Element Design

CHAPTER FOUR:

Figure 4-1. Core Thermal Performance
Figure 4-2. Turbine Thermal Performance
Figure 4-3. Condenser Thermal Performance
Figure 4-4. Radiator Tube and Fin Arrangement
Figure 4-5. Cruciform Radiator Configuration and NaK Flow Scheme
Figure 4-6. Primary and Secondary Loop Pump Thermal Performance

CHAPTER FIVE:

Figure 5-1. Comparison of Specific Impulse
Figure 5-2. J-Series 30 cm. Mercury Ion Thruster

CHAPTER SIX:

Figure 6-1. Shadow Shielding Diagram
Figure 6-2. Neutron Absorption Cross Sections for Li-6 and Li-7
Figure 6-3. Parameters Needed for Solving Shielding Dimensioning
Figure 6-4. Total Dose at Payload as a Function of Shielding Thickness and Separation Distance
Figure 6-5. Shielding Dimensions

LIST OF TABLES

CHAPTER TWO:

Table 2-1. Expected Volumes and Weights of Modules
Table 2-2. Specific NEPTUNE Mission Power Requirements

CHAPTER THREE:

Table 3-1. NEPTUNE Single Core Parameters

CHAPTER FOUR:

Table 4-1. NEPTUNE System Parameters

CHAPTER FIVE:

Table 5-1. Thruster Comparisons
Table 5-2. NEPTUNE Propulsion System Characteristics

CHAPTER SIX:

Table 6-1. Fraction of Escaping Neutrons and Gammas from the LiH Shielding
Table 6-2. Calculated Radii of the Shielding
Table 6-3. Final Shielding Parameters

CHAPTER SEVEN:

Table 7-1. System Mass Summary

CHAPTER ONE: INTRODUCTION

At the present time there are no definitive plans for a manned outer planetary mission. The goal of the NEPTUNE design is to fill this void. In order to satisfactorily explore the outer planets, a long mission time is required. Due to this fact, the mass of propellant required for chemical thrusters is prohibitive. Currently, the only system capable of providing a reasonable mission time with an acceptable propellant mass is nuclear electric propulsion. Power requirements for nuclear electric propulsion are very high for the amount of thrust necessary to achieve a reasonable mission time. In addition, the outer planets are too far from the sun to use current photovoltaic technology. As a result, the only system capable of supplying large amounts of power reliably for long periods under these conditions is a nuclear reactor.

The specific requirements for the NEPTUNE system were determined on the basis of an acceptable mission time and the required power level for the propulsion. As a reference mission, a ten year manned return voyage to Jupiter was examined. Based on the necessary thrust to meet this goal, the power level required is approximately six megawatts. Since the mission is manned, additional power requirements were provided for life support and scientific equipment. In order to provide the ability to explore further into the outer planets, a system lifetime of 20 years was specified.

The life support instrumentation and habitation facilities were selected on the basis of a five man crew. The crew positions are the spacecraft commander/pilot, reactor engineer, astrophysicist, atmospheric physicist, and planetary scientist. The responsibilities of the mission commander and reactor engineer lie with the operation and maintenance of the spacecraft, while the remaining crew members are payload specialists whose primary responsibilities are scientific exploration. Some of the specific scientific equipment to be carried by the spacecraft are an optical space telescope, a radio telescope, unmanned planetary probes, and permanent satellites for atmospheric and planetary studies. A conceptual sketch of the spacecraft is shown in Figure 1-1.

The propulsion system selected to meet the reference mission thrust requirements is a mercury bombardment type ion drive. This system was chosen on the basis of its high specific impulse and demonstrated feasibility. Since the mission lifetime exceeds the nominal thruster lifetime, surplus thrusters must be carried to provide propulsion throughout the voyage. With the ability to provide thrust throughout the voyage, two possible senarios exist. The possibilities are continuous acceleration with aero-breaking upon arrival, or acceleration toward the destination for

half the trip with deceleration during the second half.

The high power level required by the propulsion system necessitates the use of dynamic energy conversion. The Rankine cycle provides the potential for relatively high thermal-to-electric conversion efficiency and was selected for this reason. Additionally, the high temperatures needed for efficient waste heat rejection led to the selection of a liquid metal working fluid. Figure 1-2 shows the reactor system diagram.

A liquid metal coolant is boiled directly in the reactor core, and a wet mixture is sent to a pair of Ljungstrom turbines for electric power conversion. The turbine exhaust is condensed in a shell-and-tube heat exchanger to the reactor inlet temperature. The primary loop potassium is condensed in the heat exchanger tubes with a sodium-potassium (NaK) secondary fluid on the shell side. The NaK rejects the waste heat to space in a tube-and-fin radiator. Parallel centrifugal pumps are employed in both loops.

The reactor fuel is uranium nitride chosen for high thermal conductivity and high uranium density. The high uranium density corresponds to a high power density which leads to a compact core. Since the reactor operates at high temperatures for long periods of time, the primary concern of the cladding is creep strength. The molybdenum-1.25% titanium-0.25% zirconium-0.1% carbon alloy (Mo-TZC) was selected on this basis as the clad. Ljungstrom turbines are ideally suited for space application due to the fact they employ equal number of equal size counter-rotating blades so that no net torque is set up on the spacecraft. Additionally, these turbines are smaller than other turbines of equivalent power level. For these reasons, Ljungstrom turbines are employed in this system. Ljungstrom turbines can operate on a wet mixture, and are optimized for working fluids of intermediate atomic or molecular mass. Potassium meets the atomic mass requirement as well as having a low boiling point relative to other liquid metals. Potassium was selected as the working fluid on the basis of these reasons. In addition, a single loop was chosen for simplicity of design and to eliminate the mass associated with an intermediate heat exchanger.

Due to material limitations in the high temperature/high burnup environment of the reactor, two cores are needed to fulfill the mission lifetime requirements. The initial core is burned for ten years, while a standby core located within the same reactor vessel is held in a shutdown mode. After ten years, the standby core is activated, and the initial core is shut down while still immersed in flowing liquid potassium. The reactor is controlled by movable absorbing blades within the core.

The potassium from the turbine exhaust is condensed within tubes in a shell-and-tube heat exchanger by the NaK on the shell side. The volume of the secondary loop is much greater than that of the primary loop. By using NaK as the secondary fluid, good heat transfer characteristics are maintained while providing a lower mass than if potassium alone was used. The radiator

consists of rows of parallel tubes with connecting fins in a cruciform arrangement. Titanium-6% aluminum-4% vanadium was chosen as the radiator material on the basis of low material density and high strength at operating temperatures. The radiator surface is coated with calcium titanate to improve emissivity. On both the primary and secondary loops, centrifugal pumps are used to drive the flow. The pumps as well as the turbines are placed in parallel to improve system reliability.

The power conversion components as well as the remainder of the spacecraft is shielded from the reactor core by a shadow shield. Neutron moderation is achieved using lithium hydride (LiH), and gamma attenuation is accomplished using tungsten. Additional shielding is provided for the crew by placing the mercury propellant storage tank between the reactor system and the habitation modules. The modules themselves are shielded to reduce exposure from cosmic radiation. The dose to crew members due to the reactor system radiation is limited to five rem per year.

The qualitative discussion presented serves as an overview of the NEPTUNE system as a whole. All topics discussed in the report are mentioned here and developed in more detail in the following chapters. The remainder of this report is dedicated to the quantitative design and analysis of the NEPTUNE system.

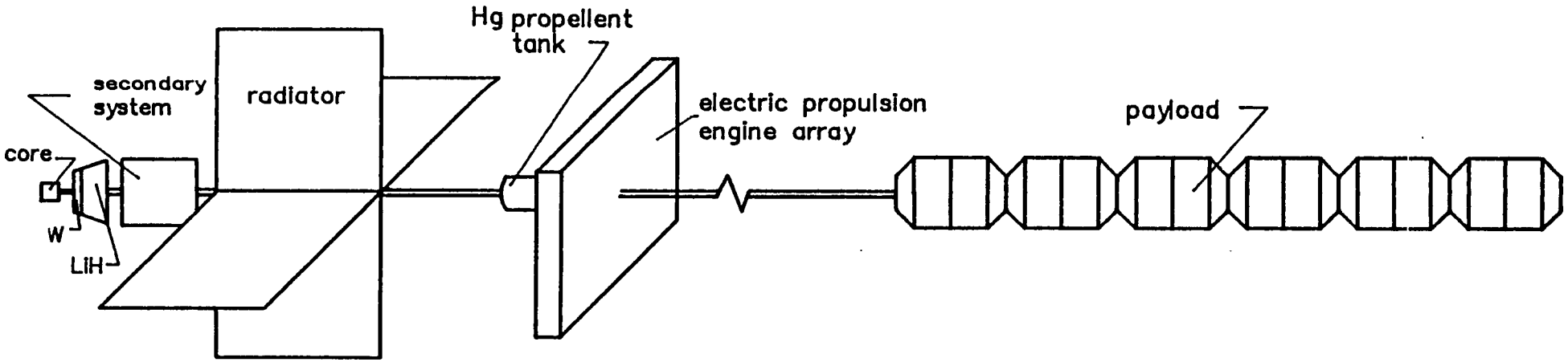


Figure 1–1 Spacecraft Schematic

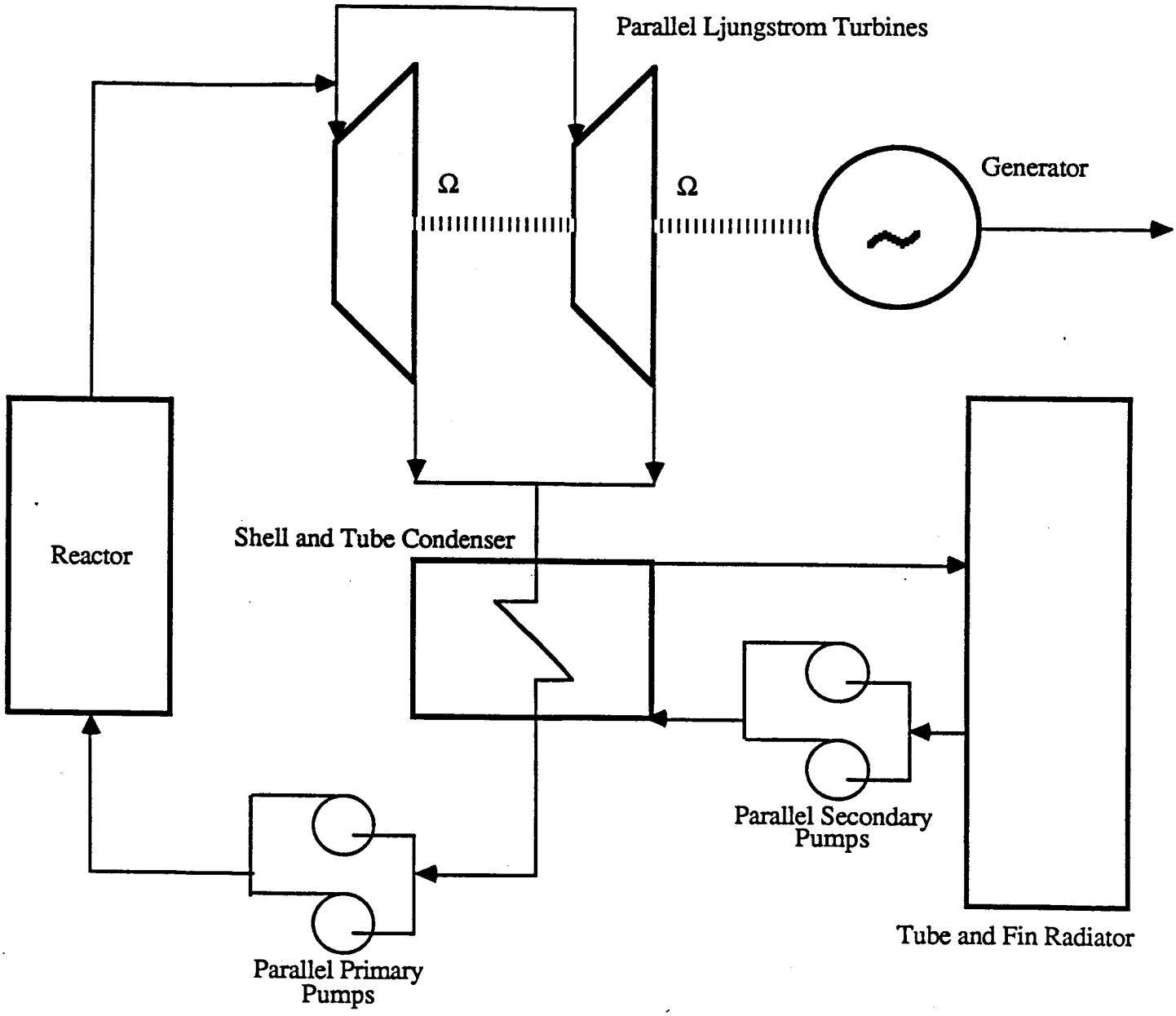


Figure 1-2 - NEPTUNE System Schematic

CHAPTER TWO: POWER REQUIREMENTS

PAYLOADS

The detailed design of the payload was not given great consideration in this report since the main emphasis is on the NEPTUNE power and propulsion systems. An estimation of the mass and power consumption is the primary purpose of examining the payload systems. The payload will consist of several modules which serve different purposes. Table 2-1 shows the expected volumes and weights that correspond with the number of segments used.

Table 2-1 - Expected Volumes and Weights of Modules

Number of Segments	Volume (m^3)	Avg Gross Mass (kg)	Maximum Gross Mass (kg)
1	77.0	12,682	15,864
2	108.9	16,455	20,591
3	140.9	19,955	24,955
4	172.9	23,273	29,091
5	204.8	26,500	33,136
6	236.8	29,727	37,227

A total of six modules should be sufficient for a crew of five. Two modules will be mission facilities which will contain the health maintenance facilities, galley, and sleeping areas. One module will be used as a command control center and will house the systems for command and life support systems. A scientific module will contain scientific equipment and laboratories. There will also be one module dedicated entirely to the CELSS system used to produce food and oxygen. The sixth module is a contingent module.

A contingent mass of 15,000 kg is added for free flying payloads, unpredicted equipment, and extra shielding. The maximum payload should be no larger than 50,000 kg and this mass is used in the needed calculations. The dimensions of the module are shown in Figure 2-1. The six modules will be connected in series as shown in Figure 2-2.

Free flyers taken along for research purposes can be attached to the outside of the modules so extra payload modules will not have to be employed. Once the destination is reached, the free flyers can be placed in a particular orbit for a time and later retrieved. Since the free flyers carry their own power source, the weight of the free flyers can be significantly reduced if they can receive

power, while deployed, from the mother ship. A possibility for this may be laser bussing of energy from the mother ship to the free flyer, and the free flyer carry some rechargable batteries for power needs when it is on the opposite side of the planet.

The particular power requirements are outlined in Table 2-2. The power levels called for in each component was either taken from literature estimates, or extrapolated from actual present-day situations.

Table 2-2 - Specific NEPTUNE Mission Power Requirements

Power Requirements	kWe
Navigation	5.0
Guidance Control	6.0
Antennas	1.0
Audio	1.0
Video	5.0
Signal Processing	2.0
Data Acquisition	1.0
System Monitoring	0.5
ECLS	11.0
EVA	7.0
Active Thermal Control	0.5
Crew Accommodations	9.0
RMS	3.0
Power Distribution	3.0
RF Systems	4.0
Tracking	3.0
Lunar Polar Orbit*	0.2
Operational Environment Satellite Follow On*	0.4
Windsat*	5.0
Controlled Ecological Life Support Systems (CELSS)	51.0
Computer Systems	100.0
Scientific Instrumentation	10.0
Radar	6.0
Health Facilities	10.0
Contingent	105.4
Total	350 kW

*These are free flying modules that will be deployed when the destination is reached. Their power consumption can be neglected during transit. At the final destination, the power to the propulsion systems will no longer be needed so that excess power can be used by these free flying modules.

The following list is a brief description of some of the more specialized capabilities of the modules described above. Again, the primary focus of the NEPTUNE study was to develop a

nuclear power/propulsion system capable of supporting a mission to the outer planets as described in Chapter 1. Beyond the power requirements of the various modules associated with the habitation of the spacecraft, no analysis was performed on any aspect of habitation design.

Lunar Polar Orbit (free flying) - Used to understand the initial conditions in the solar nebula, the process and formation and evolution for planetary bodies and evaluate the availability of lunar resources.

Operational Environment Satellite Follow On (free flying) - An environment satellite providing atmospheric sounding, continuous observations of surface, daytime visible observations, daytime and nighttime infrared observations and space environmental monitoring.

Windsat (free flying) - Provide measurements needed to describe planetary scale circulations.

Controlled Ecological Life Support Systems (CELSS) - Uses various photosynthetic organisms and both unicellular and higher plants to produce food and oxygen for the crew. It recycles 97% of the mass it contains and waste.

Scientific Instrumentation - CCD analyzer, magnetometer, plasma detectors, dust analyzers, scanning electron microscope, microwave radiometers, energetic particle detectors, etc.

Health Facilities - A facility to provide health care maintenance for the crew. Medical-surgical conditions may be work related, non-work related, unique to space flight or psychologically related to the remote environment. Also, facilities to study muscle atrophy, the cardiovascular system, and the erythropoietic system.

REFERENCES

1. Hoffman, Soldner, Friedlander, "Augmentation Program for Outer Planet Exploration: Mission Options and Requirements", Science Applications International Corporation, Schaumburg, IL, 1985

2. MacElroy, R.D., Klein, H.P., "The Evolution of CELSS for Lunar Bases", Lunar and Planetary Institute, Houston, TX, 1985.

3. Nassersharif B., Graves, M., Guetersloh S., "Space Station Power Requirements", Texas A&M University, Department of Nuclear Engineering, College Station, TX, Catalogue #16.9.

4. Roberts, B.B., "Concept for a Manned Mars Flyby", NASA-Johnson Space Center, Houston, TX, 1986.

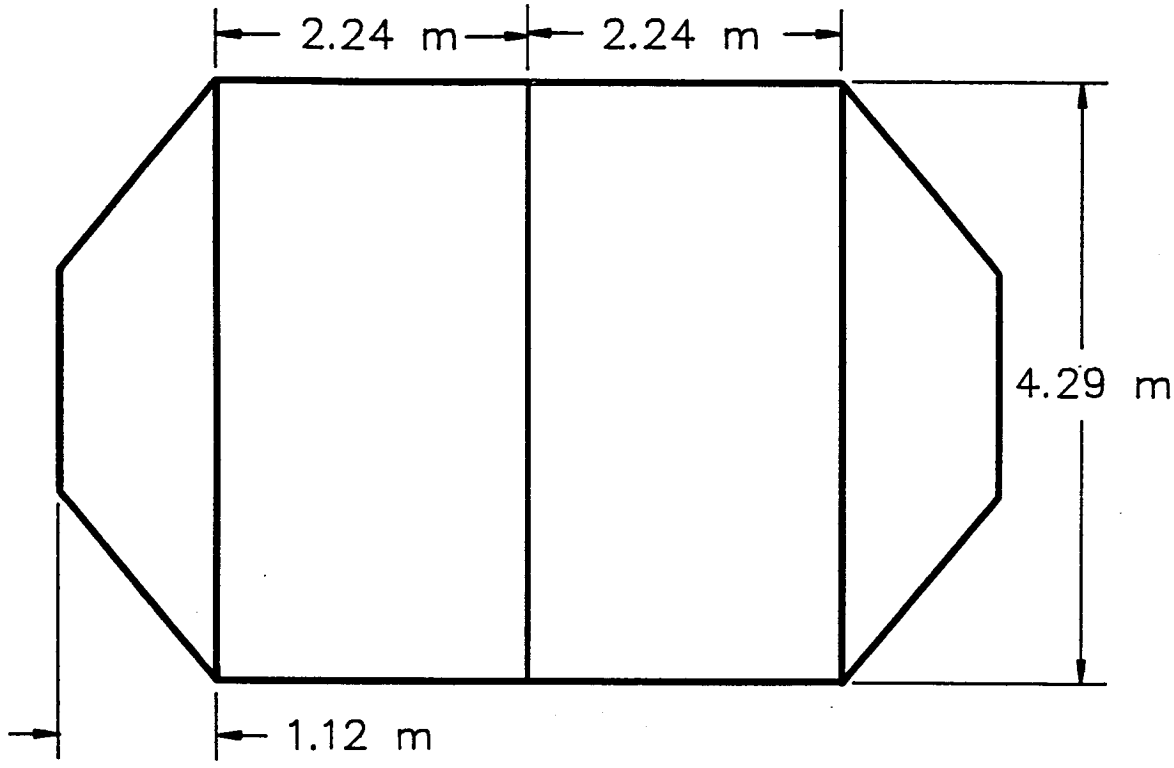


FIGURE 2-1 Dimensions of Single Module

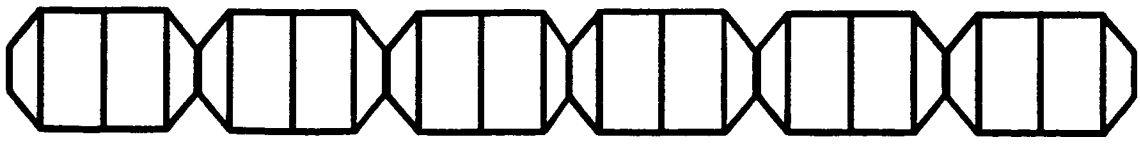


FIGURE 2-2 Module Configuration for Mission

CHAPTER THREE: CORE DESIGN

FUEL

The fuel selected for the NEPTUNE reactor is uranium mononitride (UN). The fuel was selected on the basis of several factors. The thermal conductivity of UN at the desired operating temperatures (1200K) is higher than both UO_2 and UC. Plutonium-containing fuel types were not considered due to potential danger caused by fission gas release from a clad lift-off accident. Metal fuels were not considered due to extreme swelling of fuel elements at the high burnups needed for a 10 year core life, in addition to the fact that their melting points are much lower that the ceramic fuels. Other fuel types, such as cermets were not considered because at present, they have not been adequately characterized with respect to irradiation performance. Additional benefits represented by UN are a high uranium density, which allows the construction of compact cores; and relatively low swelling at high burnup. The UN fuel also displays good compatibility with liquid metal, as well as with most molybdenum alloys.

The nitrogen present in the fuel should be enriched to a high degree in N-15. The N-14 isotope has a large cross section for the (n,p) reaction. Over a 10 year operational lifetime, a great deal of hydrogen will be built up within the fuel matrix if the N-14 is present in its natural abundance of 99.63%. The hydrogen will diffuse out of the fuel and add to the fission gases produced during operation. The resulting pressure increase overstresses the cladding. Also, the burnup of the N-14 from the absorption of neutrons causes a change in the stoichiometry of the fuel, releasing free uranium atoms. Free uranium diffuses to the clad surface and can undergo a eutectic reaction forming a low melting point alloy. This could lead to premature fuel pin failure. By enriching the nitrogen in N-15, these effects are avoided. Highly enriched nitrogen in UN is commercially available, and in fact is standard practice in these fuels.

A typical porosity value for UN fuel is 5%. The porosity is built into the fuel for the purpose of fission gas retention as well as to accommodate internal fuel swelling. Since the center of the fuel is at a higher temperature than the surrounding fuel, the central portion attempts to thermally expand more than its surroundings. This creates a high stress level in the fuel, and can cause cracking. Cracking greatly degrades thermal conductivity and increases the onset of pellet-clad interaction. When PCI occurs, microcracks in the cladding are created, which are attacked by the fission gases, causing stress corrosion cracking of the fuel elements. By providing porosity in the fuel, this effect is lessened.

Regional enrichment is also a possibility in order to flatten the flux and thus power profiles in

the core. This is a very complicated procedure and was not investigated in this study. If regional enrichment were attempted, the outer fuel pins would have a higher enrichment to bring the flux up in that area, while the central fuel pins' enrichment would be decreased to correspondingly reduce the flux in the center of the core. Axial enrichment could also be done in a similar fashion and with similar results.

CLADDING

The cladding selected is molybdenum-1.25% titanium-0.25% zirconium-0.1% carbon (Mo-TZC). The primary consideration in the selection of the clad was the creep strength, due to the high operating temperature of the reactor. To determine the lifetime of the clad, a correlation by Maag and Mattson was used to estimate the total creep strain as a function of applied stress and temperature.

$$\varepsilon = 1.026 \times 10^{-55} (\sigma)^{7.88} \exp\left\{\frac{-402628}{RT}\right\} \qquad (3.1)$$

where:

ε	=	total creep strain in /hr
σ	=	applied stress in Pa
R	=	universal gas constant in J/g-mol/K
T	=	temperature in K

The limiting creep strain was selected to be 2%. This value is the same criterion as is used for the SP-100 system. The average stress within the fuel pins was assumed to be 20MPa, again, the same as is assumed for the UN-fueled SP-100 system. At low burnup the stress will be less, while at high burnup the stress will be greater due to pellet-clad interaction. At a temperature of 1200K, the clad can withstand a stress of up to 120MPa in order to meet the creep strain limitation over a 10 year life. Alternately, for a constant stress of 20MPa, the clad will last 10 years at 2% strain at temperatures up to 1450K.

In addition to its high creep strength, the alloy displays satisfactory ductility at operating temperatures, thus reducing the possibility of a brittle fracture. There is no evidence either of hydrogen embrittlement as with tantalum alloys. The molybdenum alloys have good compatibility with both UN fuel so that no liner is required in the fuel rods. Also, compatibility with liquid potassium has been demonstrated to be very good. The structural materials present in the core and the piping for the primary loop are also composed of the Mo-TZC alloy.

COOLANT

The coolant chosen for the NEPTUNE system is liquid potassium. There are two primary reasons for this selection. The first is that potassium has the lowest boiling point of the alkali metals. At system pressures, the boiling points of the other alkali metals are too high for consideration in the system due to material limitations, and mercury possesses too low a boiling point so that the reactor would not be operating at optimum temperatures for high efficiency. The second reason for the selection of potassium is for the optimization of the Ljungstrom turbine performance.

In the radial flow Ljungstrom turbines, the amount of energy that can be extracted from the working fluid is a direct function of the magnitude of the pressure drop across the blades. The pressure drop is related to the temperature drop, and both have an effect on the density of the vapor. Thus, the pressure and temperature drop across a turbine stage is a function of the Mach number of the vapor. Low molecular weight working fluids induce high Mach numbers due to the low density of the vapor. Thus, the velocity of turbine blades on the periphery would result in stresses on the blades exceeding material limitations. High molecular weight working fluids induce low Mach numbers due to the high density of the vapor. In this case, peripheral blade velocities are within acceptable limits, but high mass flow rates are required to achieve the desired power output. Therefore, Ljungstrom turbines perform best with a working fluid of intermediate molecular weight. Coomes et al. have investigated the performance of lithium, sodium, potassium, rubidium, cesium, and mercury in conjunction with Ljungstrom turbine performance and concluded that these turbines are optimized with a potassium working fluid.

CORE GEOMETRY

Due to material limitations, it was decided to have two equivalent reactor cores to provide power for the twenty year system lifetime. Each will provide full power for ten years. During operation of the initial core, the standby core is held in shutdown mode. After ten years, the standby core is activated and brought to full power. The initial core at this point is shut down for the remainder of the mission, and is immersed in the liquid coolant flowing to the second core. Figure 3-1 shows the arrangement of the two cores with the coolant flow path indicated. The lower core was chosen to operate initially so that upon shutdown, the decay heat of the fission products may be removed by the subcooled liquid potassium entering the reactor. During operation of the initial core, the standby core is subjected to the wet mixture flow at 1200K. As a result, the clad of the standby core will be a these high temperatures for the entire twenty year mission. However, little degradation of material properties will occur, since the internal pressure on the clad will be very low. As can be seen from equation (3.1), creep strain is highly dependent on stress. Thus,

for the ten years that the standby core remains shut down, the creep strain experienced by the clad will be negligible.

Also depicted in figure 3-1 is the method of shielding the two cores from each other. Beyond the plenum length is a small section of reflecting beryllium. Between the two reflectors is a length of absorbing material similar to that used in the control blades. The total separation distance of the two cores is approximately one core height.

To guide the flow of potassium as it is boiled and expanded in the core, groups of fuel pins are contained within pressure tubes or cans. In addition, this eliminates cross-channel mixing and prevents the formation of large voids in the high power density regions near the center of the core. Also, this will allow orificing of the flow in order to help flatten the power profile across the core. Figure 3-2 shows the method of flow orificing employed. The central pressure tubes have a larger flow entrance to increase cooling in that region, since it is the hottest in the core. The flow entrance diameter decreases radially outward from the core center. The fuel pins are arranged in a hexagonal lattice in order to arrange them as closely as possible to reduce core and coolant volume. The resulting shape of the pressure tubes is that of a hexagon. This is desirable in that the stress concentration at the corners will be greatly reduced over that which would be present in a square can. Figure 3-3 shows the arrangement of three adjacent cans. A typical control blade is also indicated between the three pressure tubes. The control blades will experience a rise in temperature due to the absorption of neutrons. Argon is circulated in the regions between the pressure tubes to cool the control blades.

The overall core layout is shown in figure 3-4. Internal to the reactor vessel wall is a permanent beryllium neutron reflector. This is included for neutron economy, as well as to flatten the flux (power) profile in the reactor core. The reflector will be cooled by the circulating argon in a manner identical to that of the control blades.

CORE NEUTRONICS

The neutronics for the reactor core were calculated using the 16-group code CORE. A listing of the code is included in Appendix One. The code calculates neutron flux levels and spatial distributions from multigroup diffusion theory applied to a homogenized reactor core. The volumetric ratios of fuel, coolant, and cladding are included to account in part for heterogeneity. The 16-group cross sections for all reactor materials were obtained from Reactor Physics Constants. The Mo-TZC cladding was modeled as elemental molybdenum. The general equation for multigroup diffusion is:

$$-\left\{D_g B^2 + \Sigma_{ag} + \sum_{h-g}^{N} \Sigma(g \rightarrow h)\right\}\Phi_g + \sum_{h=1}^{g-1} \Sigma(h \rightarrow g)\Phi_h + \chi_g \sum_{h=1}^{N} \nu_h \Sigma_{fh} \Phi_h = 0 \qquad (3.2)$$

where:

N	=	number of neutron energy groups
g	=	current group
D	=	diffusion coefficient
B	=	reactor buckling
Φ	=	neutron flux
Σa	=	macroscopic absorption cross-section
Σf	=	macroscopic fission cross-section
Σ(g-h)	=	macroscopic downscattering cross-section
Σ(h-g)	=	macroscopic inscattering cross-section
χ	=	group fission neutron fraction
ν	=	number of neutrons produced per fission

Equation (3.2) is solved consecutively, beginning with group 1 flux and continuing to group 16. The resulting fluxes for the NEPTUNE reactor are shown in figure 3-5. From the calculation of the fluxes, the size of the core is determined, based on the input power and volume fractions. In order to meet the 6MWe power requirements for the propulsion system, the reactor power was set at 20MWt. This value was chosen assuming an approximate efficiency of 30%, which is typical of Rankine cycles. The core radius was calculated to be 52.97cm. The reactor core is modeled in the code as a right circular cylinder of height-to-diameter ratio of 1.0. This yields a value of 105.94cm for the core height. The fuel pin radius is specified as an input parameter. For the NEPTUNE configuration, the fuel pin radius is 0.25cm. The clad thickness, determined from the clad-to-fuel volume ratio, is 0.052cm. Using the core dimensions given, and assuming a cylindrical array of fuel pins, the fuel pin pitch is 0.70cm. This corresponds to a clearance between fuel pins of 0.20cm. The pins are wrapped with a 0.022cm diameter Mo-TZC wrap to prevent fuel rod distortion. The total number of fuel pins in the core is determined by dividing the cross-sectional area of the core by the cross-sectional area of the fuel rods, and multiplying this by the volume of the core not occupied by coolant. The resulting total number of fuel pins for the reactor is 22892 rods. The rods are arranged in a hexagonal lattice in order to place them as closely together as possible. They are in turn housed in hexagonal pressure tubes in which flows the potassium coolant as described earlier. The pressure tubes are made of the same material as the cladding. There are 289 pins in each pressure tube, corresponding to a value of 80 pressure tubes in the core. The thickness of the pressure tubes was calculated from the necessary stress to maintain a factor of safety of two over the yield stress of the Mo-TZC. The average stress on the tubes was determined from the mass flow rate and velocity of the coolant in the core. By this method, the necessary thickness was approximately 0.1cm.

The reactor vessel experiences very little stress since the only contact it has is with the

circulating argon. Therefore, the thickness of the vessel was kept as small as possible to reduce its mass. A thickness of 1cm was decided on, with the basis for the decision the ability of the vessel to withstand minor micrometeorite damage, as well as provide containment in the case of a pressure tube rupture in the core. The beryllium reflector thickness is 6cm, in order to reflect a significant amount of the fast neutrons back into the core.

The geometric buckling is calculated from the core size and is taken to be equal to the materials buckling for a critical configuration. From this information, along with the reactor power, the shape constant is determined to yield a spatial flux distribution. Due to the fact that the reactor core is modeled as a square cylinder, the resulting flux profiles are given by the following equation:

$$\Phi = AJ_o(\alpha r)\cos(\gamma z) \qquad (3.3)$$

where:

Φ = neutron flux
A = flux shape constant
α = radial buckling
r = radial position
γ = axial buckling
z = axial position

Equation (3.3) was used in conjunction with the calculated values for A and buckling to determine the spatial flux profiles. The radial flux profile is shown in figure 3-6 and the axial flux profile is shown in figure 3.7. All the fluxes given are based on a bare reactor, and are thus conservative in nature.

The value of k_{eff} is given by the last term in equation (3.2). The excess reactivity present in the core at beginning of life from this calculation is 0.1451 ($22.32). In order to keep the excess reactivity at BOL at a controllable level, the fuel enrichment was adjusted to be 40% in U-235. The total mass of UN fuel present in the system is 4000 kg/core. The critical mass of U-235 for this configuration is 1409.56kg. Knowing the power level, the consumption rate of U-235 can be calculated. The consumption rate is 6.55×10^{17} atoms/second. Knowing this, the mass of fuel consumed during the 10 year core life can be calculated. By subtracting this value from the mass of U-235 present at beginning of life, the fuel mass remaining at end of life can be determined. This value is 1423.35kg of U-235. This provides 13.79kg excess U-235 at the end of life. This corresponds to a burnup of 5.40 atom percent. UN fuels typically can accommodate burnups as high as 10% with no adverse fuel swelling or fission gas release complications.

CORE THERMAL-HYDRAULICS

The most important thermal-hydraulic consideration when boiling is to maintain at all times

the maximum heat flux in the core below the critical heat flux (CHF). At CHF the heat transfer coefficient of the coolant decreases dramatically. Exceeding the critical heat flux could thus cause overheating of fuel pins, raising clad temperatures to excessive levels. The core exit quality was specified on the basis of the amount of liquid in the wet mixture that could be accommodated by the Ljungstrom turbines, while still extracting a large amount of energy from the coolant. Based on from Coomes et al., an acceptable turbine inlet quality is 80%. This value was then chosen as the core exit quality. Since CHF decreases with increasing quality, designing the maximum heat flux in the reactor to be below CHF at 80% quality insures that the heat flux is below CHF at all locations in the core. According to Peterson, for potassium at 80% quality, the critical heat flux is 37.84 W/cm^2. This was determined from a curve fit to experimental data. The data and correlation are shown in figure 3-8.

The maximum volumetric heat generation rate was determined by calculating the fission rate for each group, summing them, and multiplying by the energy released per fission (200MeV/fission for U-235). This value is then divided by the core volume and the fuel fraction. Maximum q''' for the NEPTUNE reactor was calculated to be 243.01 W/cm^3. The maximum heat flux is then calculated from the following relationship:

$$q''(2\pi R_{rod}L) = q'''(\pi R_{rod}^2 L) \qquad (3.4)$$

where:

q'' = maximum heat flux
q''' = maximum volumetric heat generation rate
R = radius of the fuel rod
L = length of the fuel rod

Using equation (3.4), the maximum q" was determined to be 30.38 W/cm^2. This value is below the most restrictive value of CHF for the system. Therefore the heat flux at all points within the core is within acceptable limits, and no degradation of the potassium heat transfer coefficient will occur. To illustrate the extent to which the maximum heat flux is below CHF is illustrated by the fact that the Departure from Nucleate Boiling Ratio (DNBR) for the maximum heat flux is 1.22.

The average linear heat rate is calculated by dividing the reactor power by the total active fuel length in the core. This amounts to dividing the reactor power by the height of the core and the total number of fuel rods. The result is a q' of 8.25 W/cm. The average heat flux can be determined in a manner similar to equation (3.4) by the following expression:

$$q'L = q''(2\pi R_{rod}L) \qquad (3.5)$$

where q' is the average linear heat rate and all other variables have been defined previously. The average heat flux calculated from equation (3.5) is 5.25 W/cm^2.

The power profile in the reactor bears the same shape as that of the flux. Using the maximum and average heat fluxes, the radial and axial power profiles were generated in the same manner as the flux profiles using equation (3.3). The average and hot channel axial power profiles are given in figure 3-9. The radial power profile is given in figure 3-10. It can be seen that due to the very low average values, the average power distribution in the core is fairly uniform in both the radial and axial directions.

The temperature profile in the fuel rods was determined under two conditions, before and after fuel-cladding gap closure. The temperature profile before gap closure was determined using TDC1MOD2, which uses a thermal resistance model of the cylindrical fuel pins to calculate temperatures at various locations within the fuel rod. A complete listing of this code is available in Appendix One. With a 0.0035cm helium-filled gap, and the other dimensions given previously, the fuel radius is 0.1945cm. Using the maximum heat flux calculated earlier, and estimating the outer clad temperature at 1200K, the temperature distribution falls as shown in figure 3-11. The maximum centerline fuel temperature under these conditions is 1234.35K.

After gap closure, the temperature profile was calculated using a thermal resistance model by El-Wakil. Bond and Converse report a correlation of Nusselt number as a function of quality for potassium. This correlation is shown in figure 3-12. At 80% quality and 1200K the Nusselt number is 120. Using the following expression, the heat transfer coefficient (h) was calculated:

$$h = \frac{(Nu)k_f}{L} \tag{3.6}$$

where k_f is the fluid thermal conductivity. The resulting heat transfer coefficient is 3175 W/m^2-K. For the thermal conductivity of the fuel, the Hayes-Thomas correlation was used which is:

$$k = 1.864(\exp\{-2.14P\}T^{0.361} \tag{3.7}$$

where P represents the porosity of the fuel. Evaluation of this expression at a temperature of 1250K and 5% porosity UN yields a thermal conductivity of 23.47 W/m-K. The thermal conductivity of the cladding was modeled as that of elemental molybdenum. A correlation was developed, and is given in the following expression:

$$k = 1.5275 - 5.100 \times 10^{-4}(T) + 9.734 \times 10^{-8}(T)^2 \tag{3.8}$$

Evaluation of equation (3.8) at 1225K yields a thermal conductivity of the clad of 104.20 W/m-K.

Knowing the dimensions of the fuel pin, and using the results from the given correlations, the thermal resistance of the fuel, clad, and coolant was determined. El-Wakil's thermal resistance model is given by the following equation:

$$q_s = \frac{T_{Cl} - T_f}{\frac{R}{2k_f A_R} + \frac{c}{k_c A_m} + \frac{1}{hA_{R+c}}} \qquad (3.9)$$

where:

q_s = heat production in W
T_{Cl} = fuel centerline temperature
T_f = coolant temperature
R = fuel pellet radius
c = cladding thickness
k_f = fuel thermal conductivity
k_c = cladding thermal conductivity
h = coolant heat transfer coefficient
A_R = fuel surface area
A_m = surface area of fuel rod
A_{R+c} = log mean average surface area of rod and fuel pellet

Using this model, the maximum fuel centerline temperature after gap closure was calculated to be 1228.31K. Using an average coolant temperature of 1000K, the average fuel centerline temperature is 1007.80K. While these temperature may seem low, it must be kept in mind that in order to stay below CHF at all times, the average heat flux is quite low as a result. For comparison, in an LWR, the average linear heat rate is on the order of 175 W/cm. This compares to 8.25 W/cm for the NEPTUNE reactor. In addition at NEPTUNE operating temperatures, the thermal conductivity of UN is approximately a factor of ten greater than that of UO_2. This is the reason LWR fuel centerline temperatures are normally in excess of 3000K.

To determine the point at which the bulk coolant begins nucleate boiling, the following expression is used to determine the heat flux at that location:

$$q'' = h\{T_w(z) - T_b(z)\} \qquad (3.10)$$

T_w is assumed to be ~2K above the saturation temperature of 1200K. T_{bulk} is at saturation at this point, and all points up the channel. The heat flux at this location is then related to the axial power profile given in figure 3-9. The point at which bulk nucleate boiling begins is 7cm from the core entrance.

FUEL ELEMENT DESIGN

As was stated earlier, the fuel rod radius was selected to be 0.25cm. On the basis of the volume fractions given for the fuel, cladding, and coolant, and the mass of fuel present in the core, the cladding thickness was found to be 0.052cm. In order to determine the gap width in the fuel

element, it was necessary to calculate the amount of fuel swelling expected over the 10 year core life. For this purpose, the Thomas-Brozak correlation for UN fuel swelling was used:

$$\frac{\Delta V}{V} = 3.654 \times 10^{-7}(T^{1.138})(B^{0.6615})(SD^{-1.115})(FD^{2.816}) \qquad (3.11)$$

where:

$\Delta V/V$	=	fuel swelling
T	=	fuel average temperature
B	=	burnup in atom percent
SD	=	smear density
FD	=	fuel density as percent of theoretical

In equation (3.11), the fuel average temperature was taken to be 1230K on the basis of the temperature profiles given earlier. The smear density (ratio of fuel area to total area within the clad) was taken to be 90%, and the fuel density was taken to be 95% as was done for earlier calculations. The swelling expected for the fuel under these conditions is shown as a function of burnup in figure 3-13. The point at which gap closure is desired was selected on the basis of when the swelling ceases to be as strong a function of burnup. End of life burnup in the NEPTUNE reactor is 5.40%. The gap closure swelling was chosen to be 5%, corresponding to a burnup of 2.18 atom percent. The swelling experienced by the fuel beyond this point will not overstress the cladding.

To determine the gap thickness necessary to insure closure at 5% fuel swelling the following expression for swelling was used to relate $\Delta V/V$ to the inner diameter of the fuel pin:

$$\frac{\Delta V}{V} = \frac{3\Delta D}{D} \qquad (3.12)$$

where $\Delta D/D$ represents the change in fuel diameter over the original fuel diameter. Setting the right hand side of equation (3.12) equal to 5%, and solving for the initial diameter yields a value of 0.389cm. This corresponds to a cold gap width of 0.0035cm. The hot gap width at beginning of life is determined from the following equation:

$$t_{hot} = t_{cold} + R_{fuel}\left\{\alpha T_c - \frac{1}{2}\alpha_f(T_o - T_s)\right\} \qquad (3.13)$$

where:

t_{hot}	=	hot gap width
t_{cold}	=	cold gap width
R_{fuel}	=	radius of the cold fuel pellet
α	=	thermal expansion coefficient of the cladding
α_f	=	thermal expansion coefficient of the fuel
T_c	=	average temperature of the clad
T_o	=	fuel pin outer temperature
T_s	=	fuel centerline temperature

The thermal expansion coefficient of the fuel was obtained from Matzke. The thermal expansion

coefficient for the clad was taken from Tietz and Wilson. Once again, the cladding was modeled as molybdenum. Using equation (3.13), the hot gap width was found to be 0.0034cm at BOL. Since the temperature rise across the fuel pin is very mild, the thermal expansion effects are essentially negligible compared to the fuel swelling. Thus, PCI should not occur sooner than the 2.18 atom percent burnup mentioned earlier. This corresponds to a time of 4.04 years to gap closure. A cross-section of a fuel pin is shown in figure 3.14.

The fission gas plenum volume in the fuel elements was determined from the amount of fission gases released over the 10 year core life. To determine fission gas release, the Thomas-Brozak correlation was used:

$$FGR = 6.271 \times 10^{-5}(T^{3.068})(B^{0.4531})(FD^{-2.454}) \qquad (3.14)$$

where FGR is the percent fission gas release, and all other variable are as defined previously. Inserting the same values as for the fuel swelling, and a burnup of 5.40% corresponding to the end of life, the fission gas release was found to be 6.0%. Knowing the number of fissions over the core life, the number of fission products can be found by multiplying the number of fissions by two. Using values of fission product yield given by Oleander, the number of fission gases produced over the core life can be found. The primary gases of concern are xenon and krypton which together represent a yield of 0.251. Multiplying the number of fission gas atoms produced by the fission gas release, the number of gas atoms escaping the fuel can be found. By dividing by Avogadro's number, the number of moles of fission gases in the plenum can be found. By employing the following equation, the necessary volume of the plenum can be determined:

$$V_{plenum} = \frac{nRT}{P_g} \qquad (3.15)$$

where:

V	=	required plenum volume
n	=	number of moles of gas
R	=	universal gas constant
T	=	temperature of the plenum
P_g	=	internal pressure of the plenum

The plenum internal pressure was specified to be the same as the pressure external to the pin, namely, the saturation pressure of the potassium coolant at 1200K. Using the values calculated previously, the necessary plenum length was found to be 27.8cm. This was divided into two regions, one above and one below the active core, each 13.9cm long. Figure 3-15 shows a vertical elevation of a fuel element.

REACTOR CONTROL

To calculate control rod worth in a fast reactor is a very simple matter. Since the absorber used, in this case B_4C, is primarily a thermal neutron absorber, the perturbation of the fast flux in the region of the control blade is minimal. For this reason, the control rod material can be averaged over the entire core volume, and all control rod worths added together to give the total rod worth. The excess reactivity at beginning of life is \$22.32 for the bare configuration. In order to assure a satisfactory shutdown margin with the beryllium reflector in place, the total rod worth was chosen to be \$35.00.

By using the following equation, the worth of a single rod can be determined:

$$\rho_w = \frac{\Sigma_a^b}{\Sigma_a^f + \Sigma_a^c} \tag{3.16}$$

which is merely the macroscopic absorption cross-section of the absorber in the control blade divided by the sum of the macroscopic absorption cross-sections of everything else in the core. Using equation (3.16), the worth of a single blade was found to be \$1.22. For a total rod worth of \$35, 29 rods must be used. The rods are a blade-type shape and are shown in figure 3-3. The blades are 0.5cm wide, 12 long, and 104cm tall. The blades are sheathed in the same Mo-TZC alloy as is used for the clad material. The blades are driven using standard control blade drives. In addition to moving the blades for control purposes, they can also be adjusted to help flatten the power profile in the core.

SUMMARY

The methods used to calculate all the important parameters for the NEPTUNE core are included in this section, along with the pertinent formulas and references. Table 3-1 lists explicitly the most important values specified and calculated for the reactor core, including neutronic and thermal-hydraulic factors. A complete list of references used for the core design is available at the end of this chapter as well. Listings of the codes CORE and TDC1MOD2 are available in Appendix One.

REFERENCES

1. Bond, J.A., Converse, G.L., "Vaporization of High-Temperature Potassium in Forced Convection at Saturation Temperatures of 1800 to 2100 °F", NASA CR-843, 1967.

2. Brozak, D.E., "TDC1MOD2: A Steady-State Fuel Pin Temperature Distribution Code", written for the Advanced Nuclear Fuels Laboratory, Texas A&M University, 1987.

3. "Chart of the Nuclides", 13th edition, General Electric Co., San Jose, CA, 1984.

4. Coomes, E.P., et al., "Design of a High-Power-Density Ljungstrom Turbine Using Potassium as a Working Fluid", American Power Conference.

5. DiStefano, J.R. "Review of Alkali Metal and Refractory Alloy Compatibility for Rankine Cycle Applications", Fifth Symposium on Space Nuclear Power Systems, Albuquerque, NM, 1988.

6. El-Wakil, M.M., Nuclear Heat Transport, International Textbook Co., Scranton, PA, 1971.

7. Griffith, R., "CORE: A Fast Reactor Core Design Code", written for NUEN 622, Texas A&M University, 1985.

8. "Handbook of Chemistry and Physics", 68th edition, CRC Press, Boca Raton, FL, 1987.

9. Horak, J.A., "Load Carrying Capabilities of Selected Refractory Alloys for Space Nuclear Power Applications", Second Symposium on Space Nuclear Power Systems, Albuquerque, NM, 1985.

10. Incropera, F.P., DeWitt, D.P., Fundamentals of Heat and Mass Transfer, John Wiley and Sons, New York, NY, 1981.

11. Lamarsh, J.R., Introduction to Nuclear Reactor Theory, Addison-Wesley Publishing Co., Reading, MA, 1966.

12. Lamarsh, J.R., Introduction to Nuclear Engineering, Addison-Wesley Publishing Co., Reading, MA, 1983.

13. Maag, W.L., Mattson, W.F., "Statistical Analysis of High Temperature Creep Rate Data for Alloys of Tantalum, Molybdenum, and Columbium", NASA TND-5424, 1969.

14. Matzke, Hj., Science of Advanced LMFBR Fuels, North-Holland Publishing Co., Amsterdam, Holland, 1986.

15. "Neutron Cross Sections", BNL-325, Volume 3, 1965.

16. Olander, D.R., Fundamental Aspects of Nuclear Reactor Fuel Elements, Technical Information Center, USDOE, 1976.

17. Peterson, J.R., "High-Performance "Once-Through" Boiling of Potassium in Single Tubes at Saturation Temperatures of 1500 to 1750 °F", NASA CR-842, 1967.

18. "Reactor Physics Constants", USAEC Report ANL-5800, 1963.

19. Rust, J.H., Nuclear Power Plant Engineering, S.W. Holland Co., Atlanta, GA, 1979.

20. "Standard Mathematical Tables", 27th edition, CRC Press, Boca Raton, FL, 1984.

21. Thomas, J.K., Brozak, D.E., Hayes, S.L., Peddicord, K.L., "Material Property and Irradiation Performance Correlations for Nitride Fuels", Fifth Symposium for Space Nuclear Power Systems, Albuqeurque, NM, 1988.

22. Tietz, T.E. , Wilson, J.W., Behavior and Properties of Refractory Metals, Stanford University Press, Stanford, CA, 1965.

Table 3-1: NEPTUNE single core parameters

NEUTRONICS:

Enrichment	40% in U-235
Fuel Mass	4000 kg
U-235 Critical Mass	1409.56 kg
U-235 Mass at EOL	1423.45 kg
Total Flux (over core volume)	3.80E+14 n/cm^2-s
Fluence at EOL	1.20E+23 n/cm^2
Excess Reactivity at BOL	$22.32
Total Control Rod Worth	$35.00
Burnup at EOL	5.40 atom percent

GEOMETRY:

Core Radius	52.97 cm
Core Height	105.84 cm
Geometric Buckling	0.0029 1/cm^2
Total Number of Fuel Pins	22892
Fuel Pin Radius	0.25 cm
Fuel Pins/Pressure Tube	289
Clad Thickness	0.052 cm
Cold Gap Thickness	0.0035 cm
Fuel Rod Pitch	0.70 cm
Wire Wrap Diameter	0.14 cm
Wire Wrap Helical Pitch	27.94 cm
Plenum Length	27.8 cm

THERMAL-HYDRAULICS:

Reactor Thermal Power	20 MWt
Maximum Heat Flux	30.38 W/cm^2
Average Heat Flux	5.25 W/cm^2
Linear Heat Rate	8.25 W/cm
Coolant Inlet Temperature	780 K
Coolant Exit Temperature	1200 K
Coolant Exit Quality	0.8
Peak Fuel Centerline Temperature	1235 K

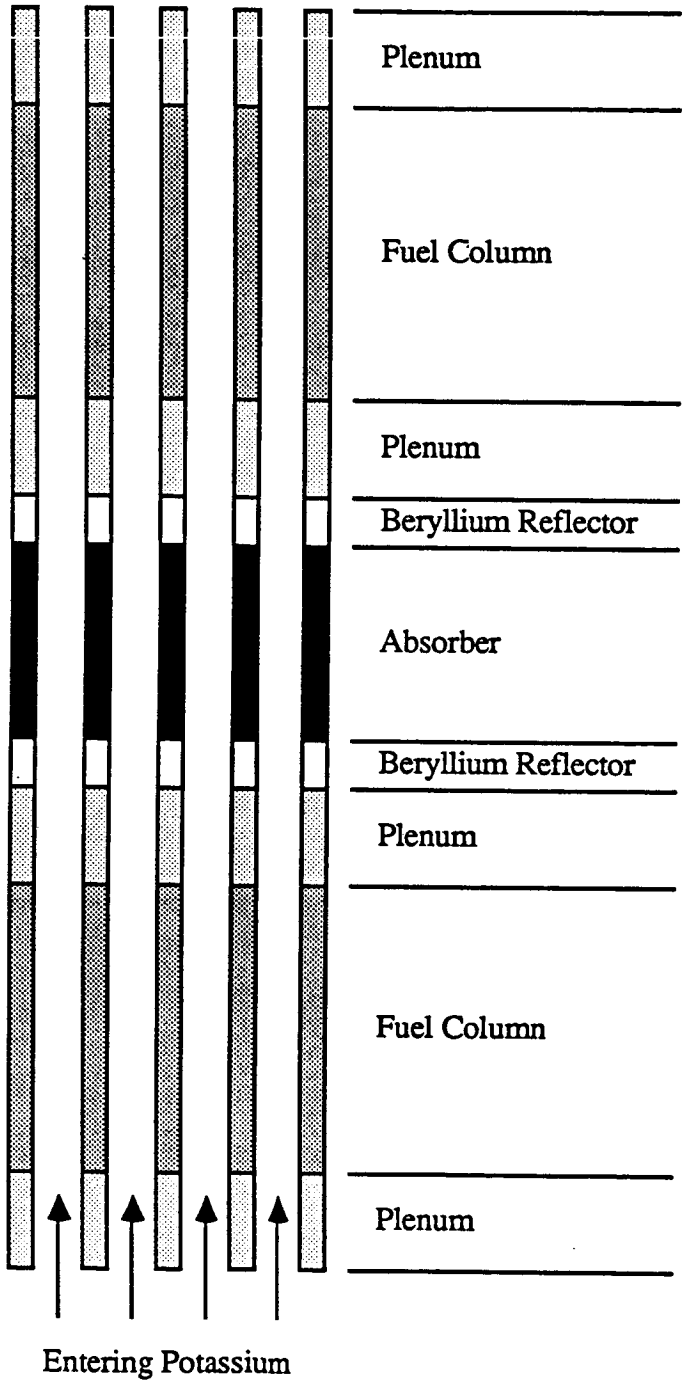


Figure 3-1. Two-Core Configuration.

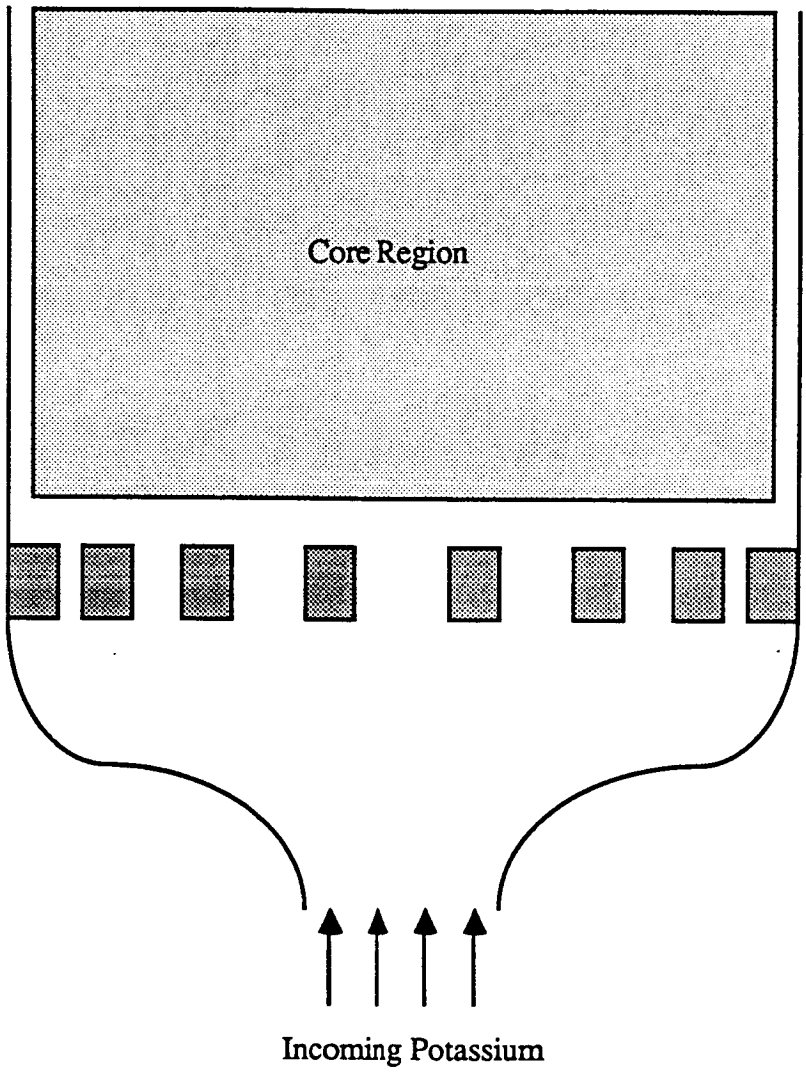


Figure 3-2. Coolant Orificing Scheme.

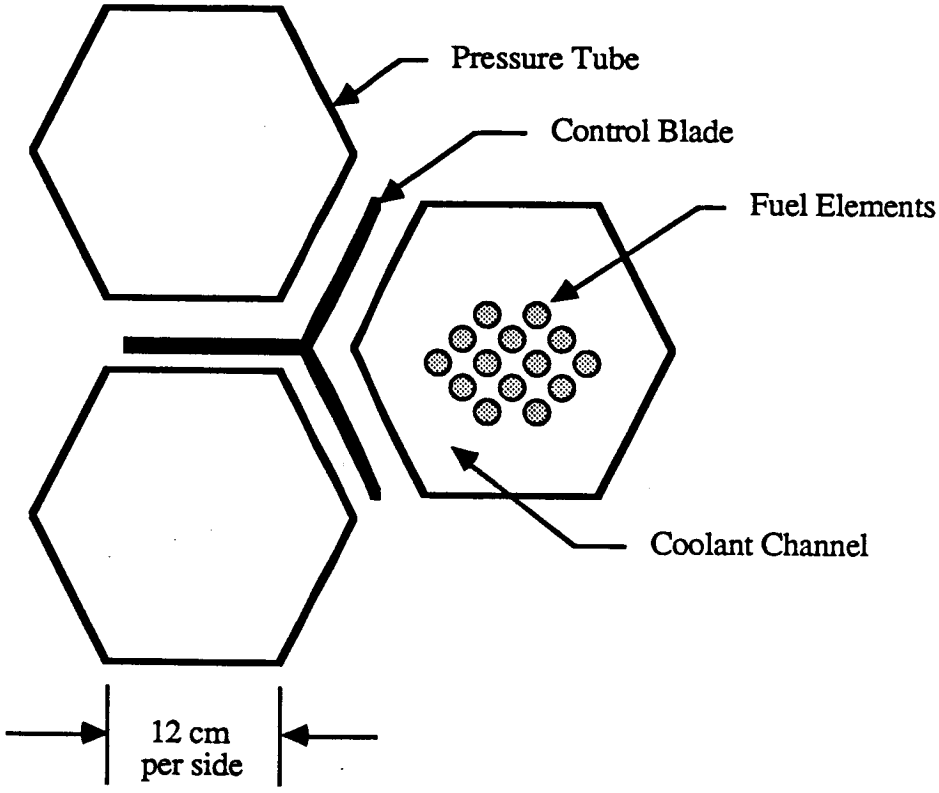


Figure 3-3. Pressure Tube and Control Blade Arrangement.

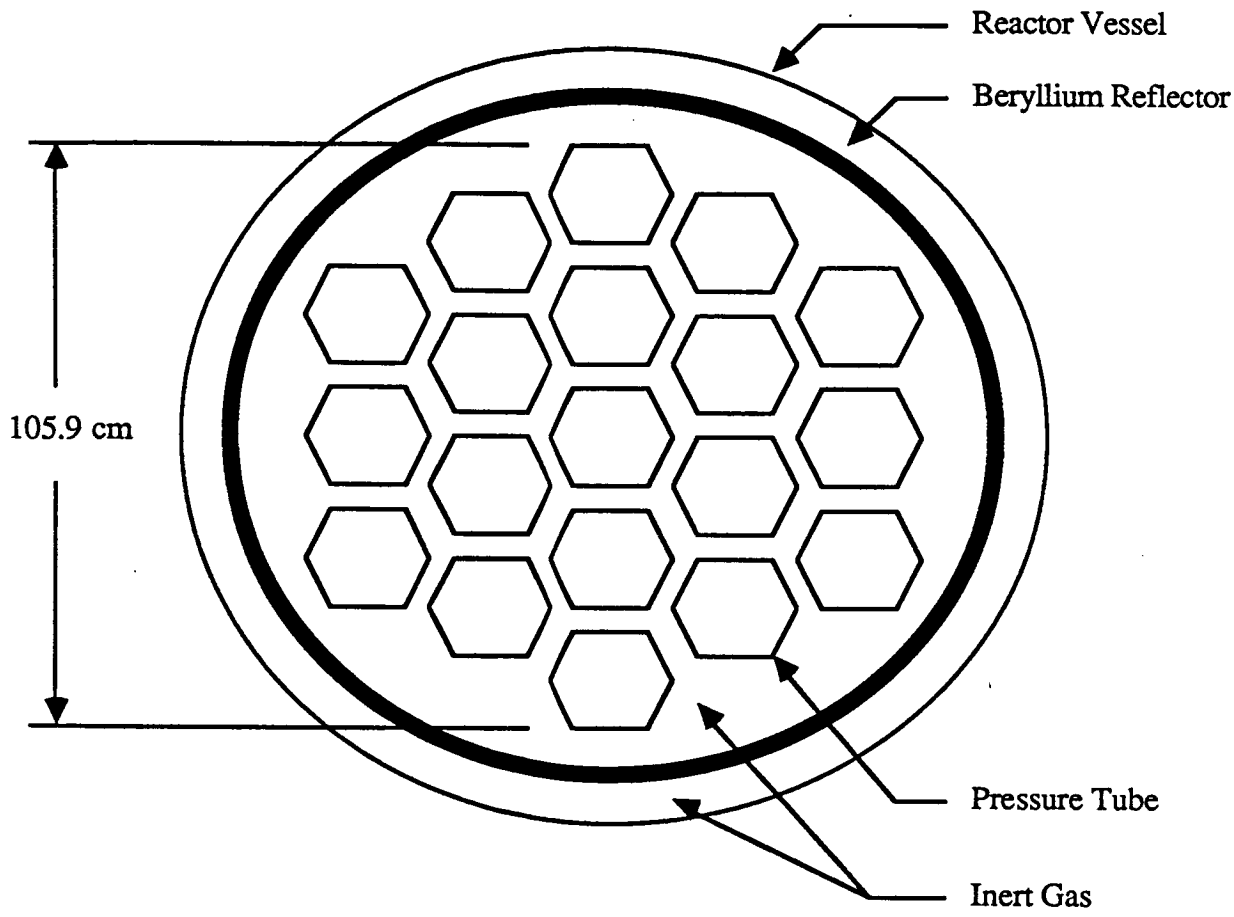


Figure 3-4. Reactor Cross Section.

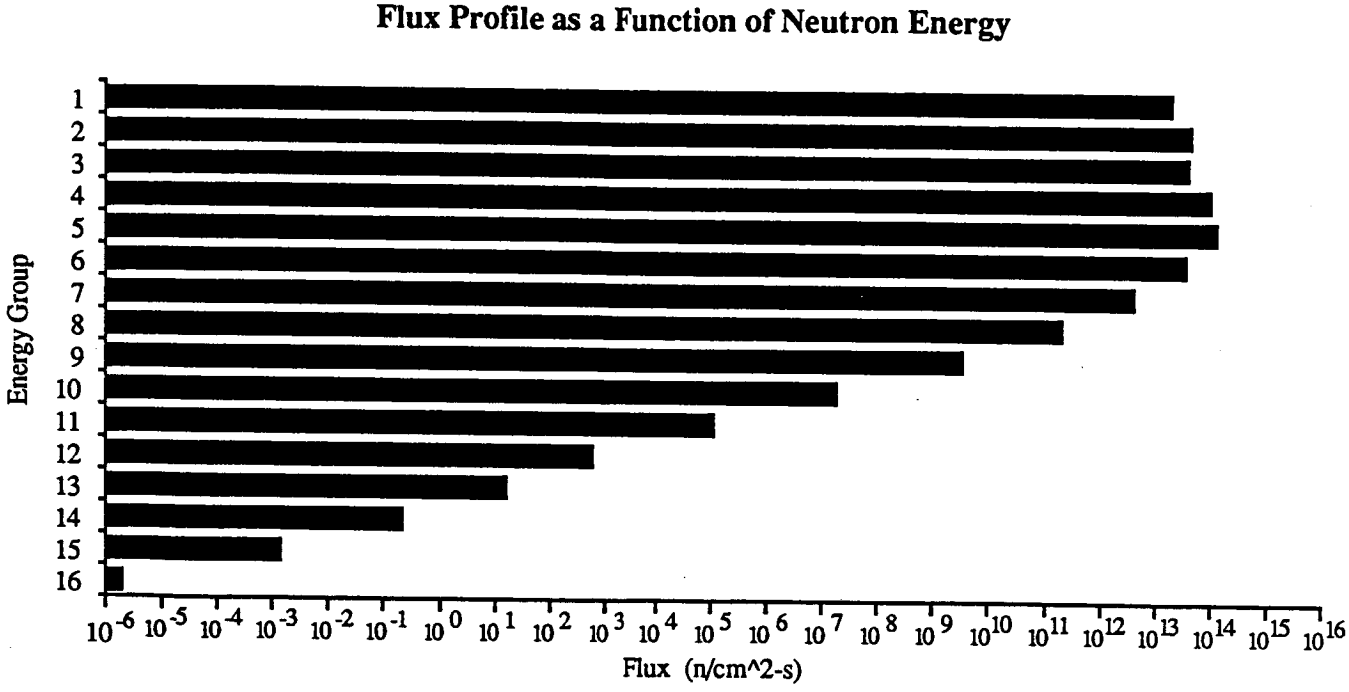


Fig. 3-5 - Flux Distribution as a Function of Energy Group

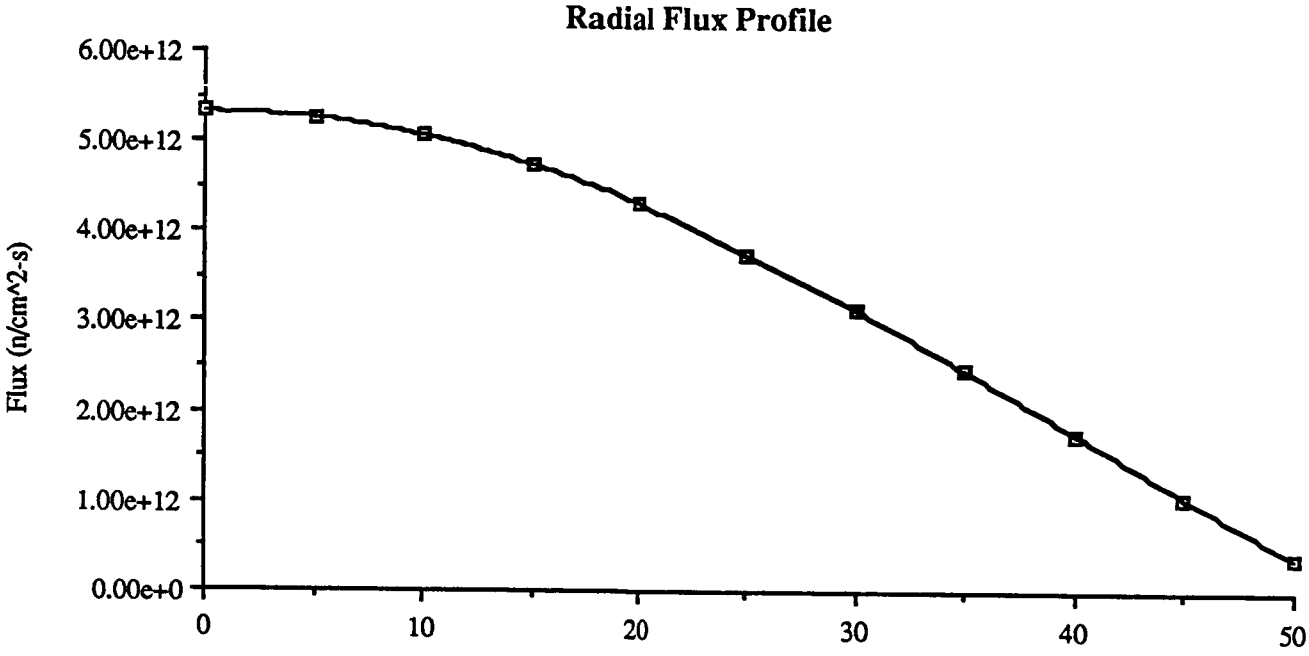


Fig. 3-6 - Radial Flux Profile

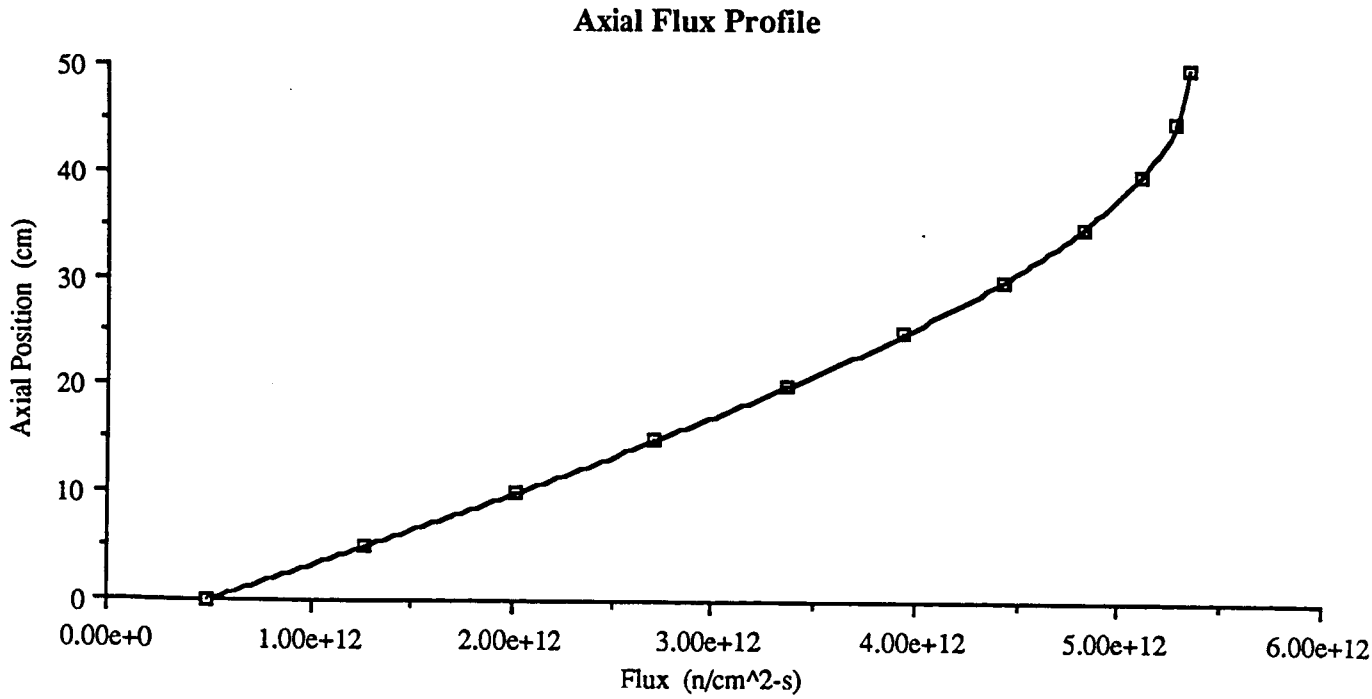


Fig. 3-7 - Axial Flux Profile from Core Inlet to Midplane

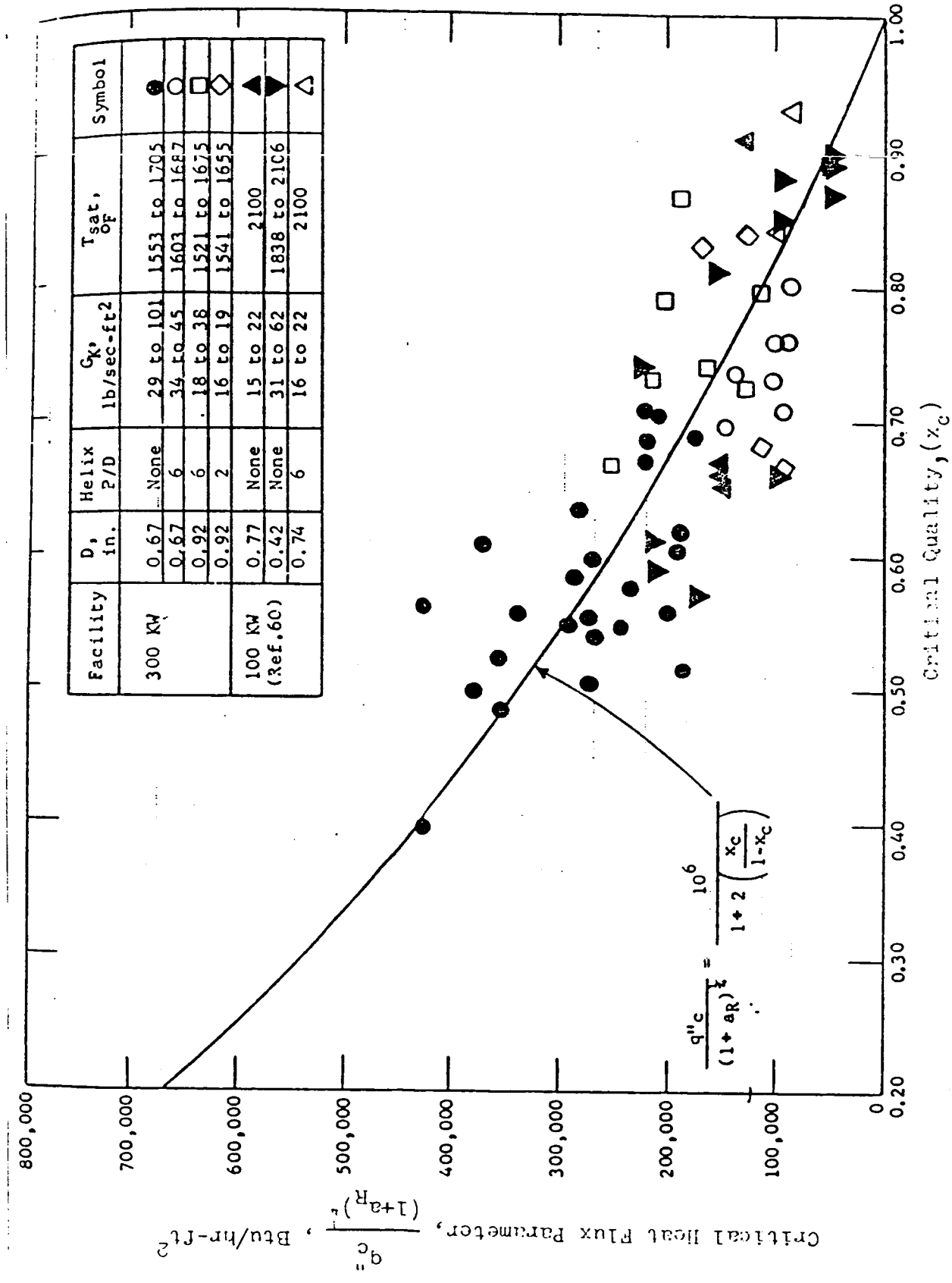


Figure 3-8. Critical Heat Flux as a Function of Quality.

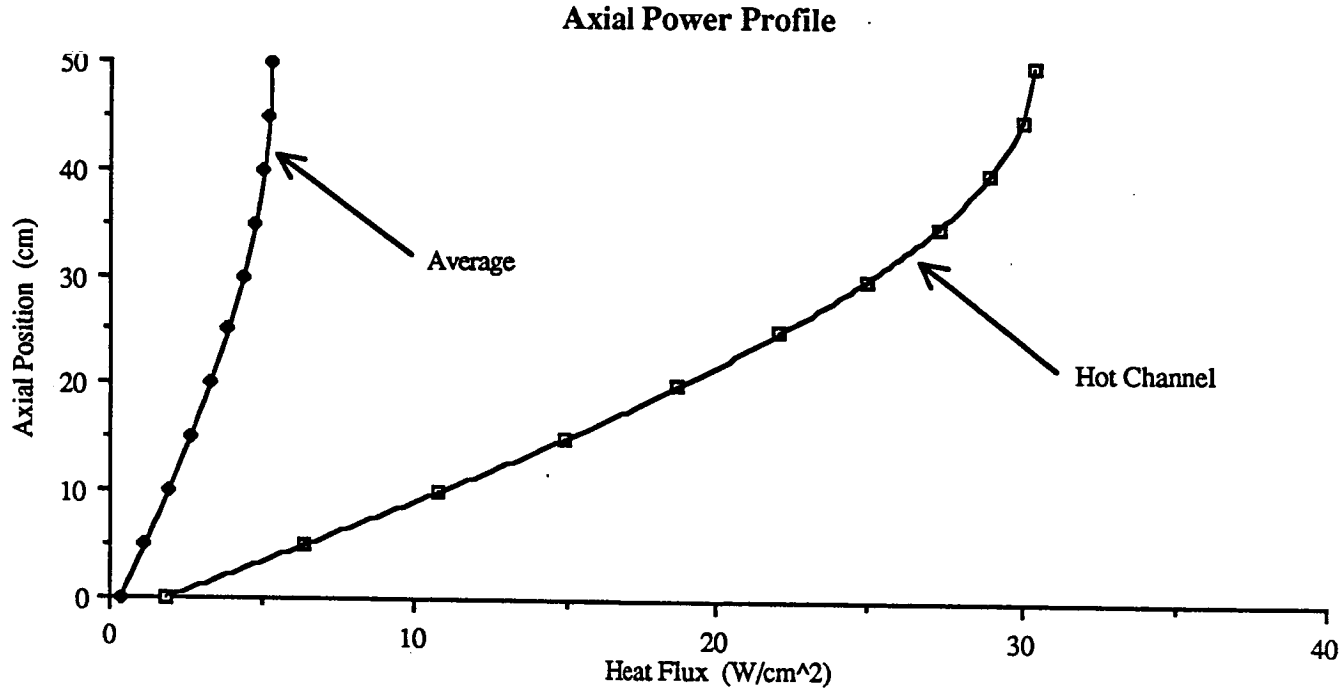


Fig. 3-9 - Axial Power Profile Showing Both Average and Hot Channel Heat Flux

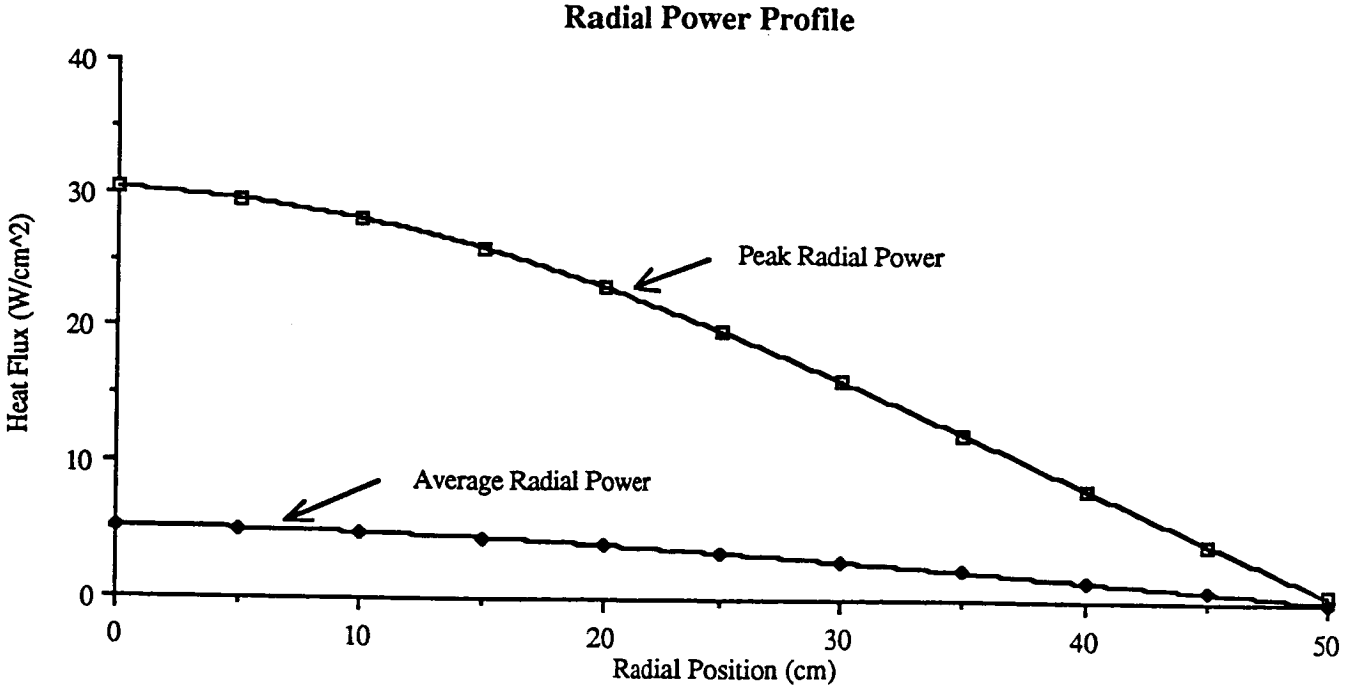


Fig. 3-10 - Radial Power Profile Showing Both Average and Peak Heat Flux

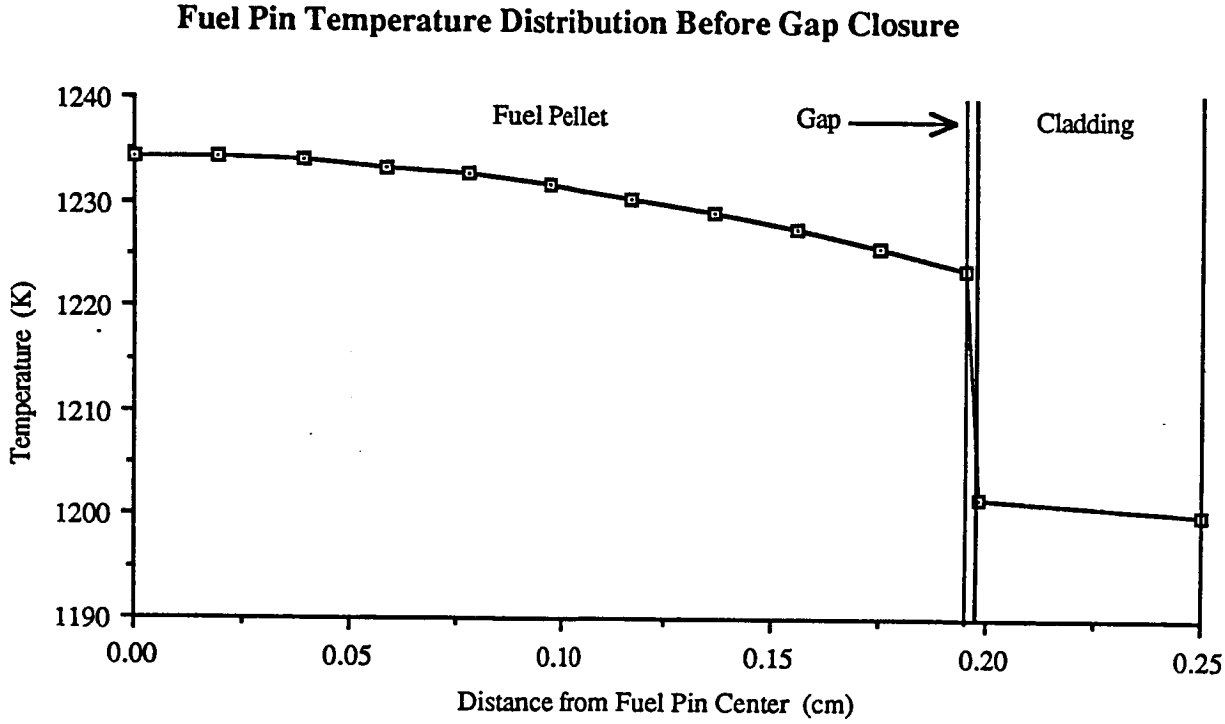


Fig. 3-11 - Temperature Distributions in Fuel Element Before Gap Closure

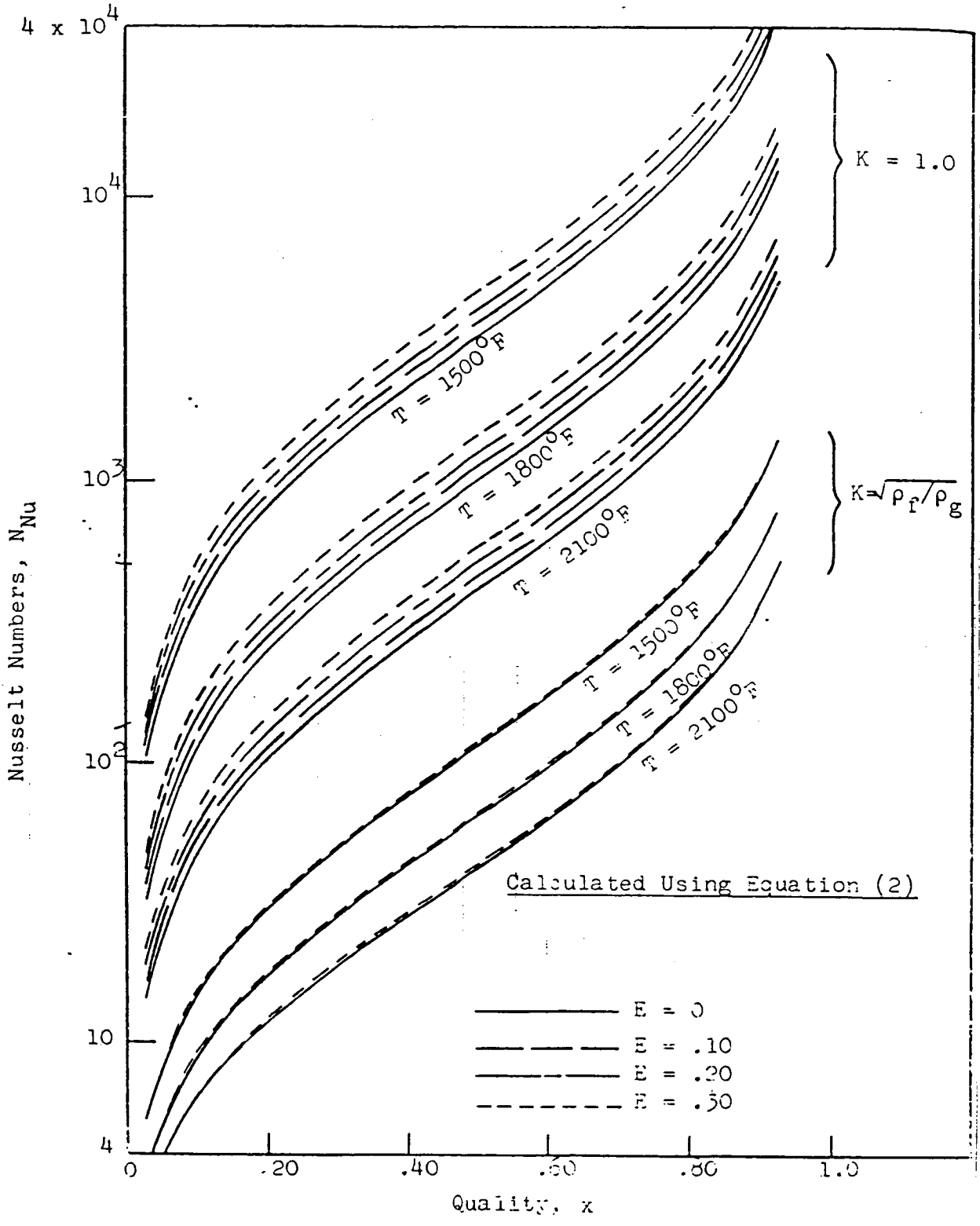


Figure 3-12. Nusselt Number as a Function of Quality.

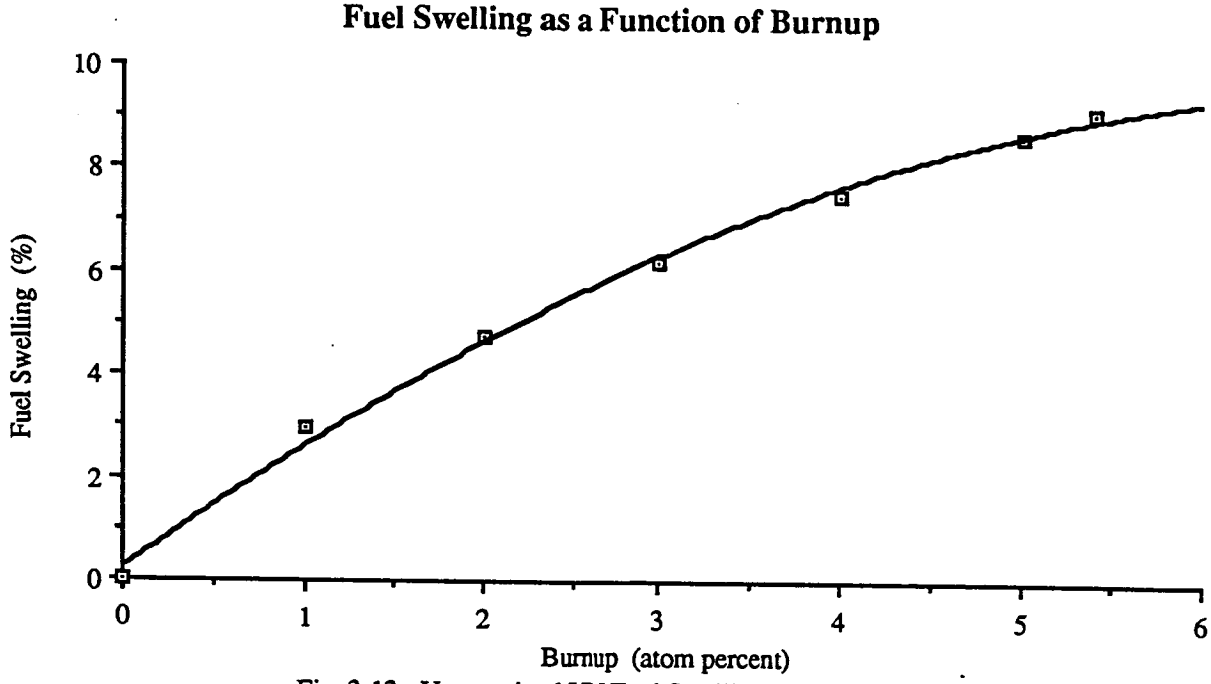


Fig. 3-13 - Unrestrained UN Fuel Swelling as a Function of Burnup

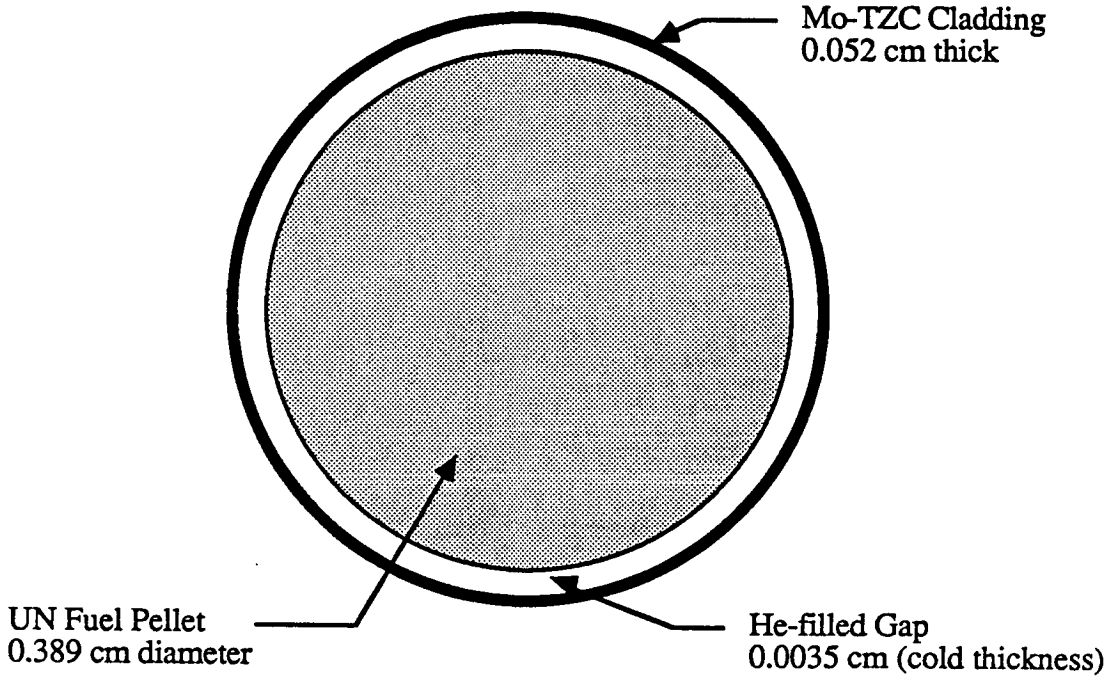


Figure 3-14. Fuel Pin Cross Section.

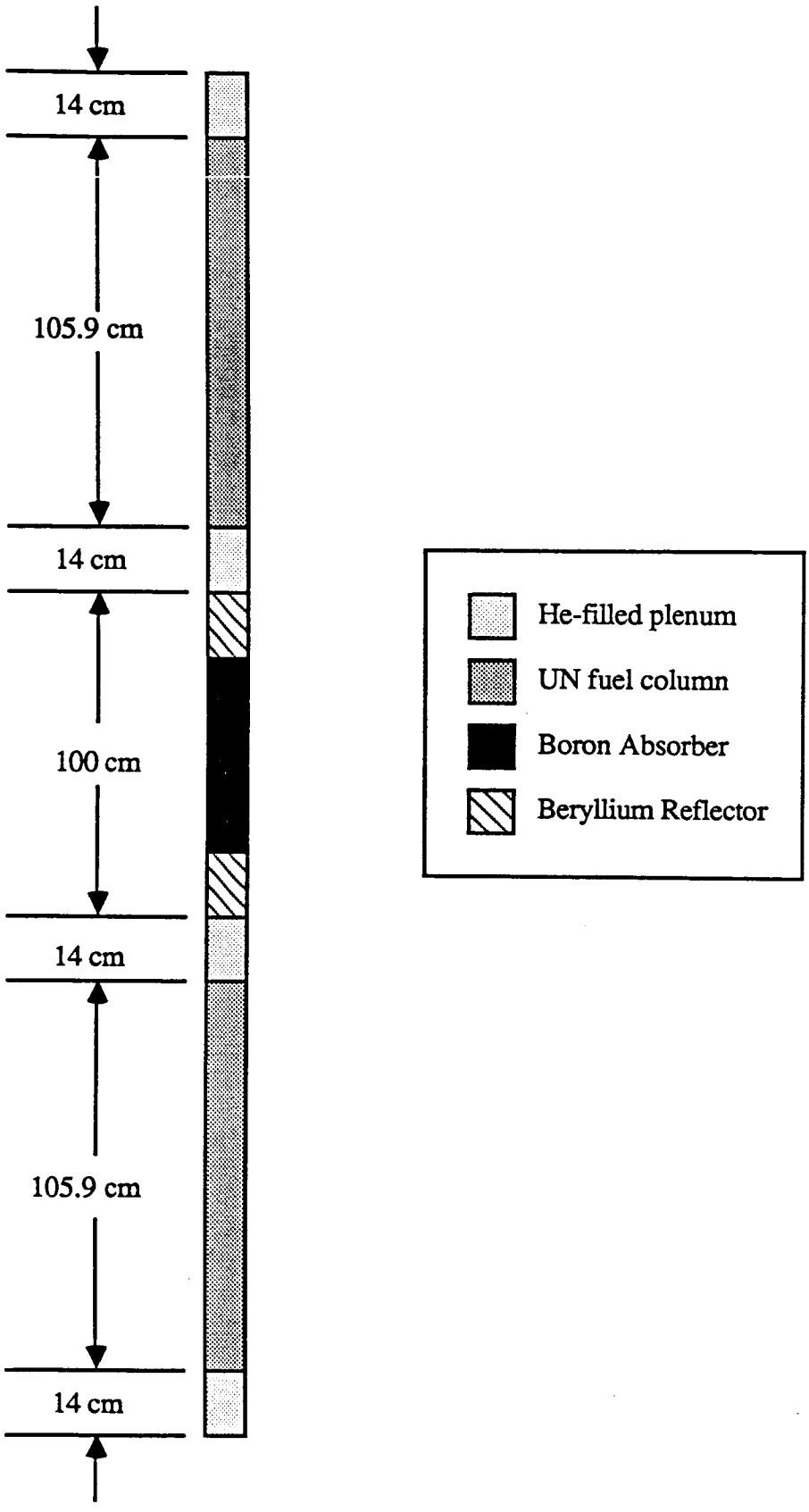


Figure 3-15. Vertical Fuel Element Design.

CHAPTER FOUR: SYSTEM ANALYSIS

The basic NEPTUNE system diagram was shown previously as figure 1-2. In the NEPTUNE power conversion system, potassium enters the reactor vessel in a subcooled state. The potassium is boiled as travels through the core pressure tubes and exits as a wet mixture of approximately 80% quality. The wet mixture is split equally and sent to a pair of Ljungstrom turbines for electrical power conversion. The wet mixture enters the turbine at essentially the same condition as the core outlet, and is expanded through the turbines to drive the turbine shaft which is connected to the turbine-generators for the generation of electrical power. The coolant is exhausted from the turbine at a state of low pressure and lower temperature and quality.

At this point, the turbine exhaust is sent to a counterflow shell-and-tube heat exchanger. The wet potassium mixture is first condensed and then subcooled within the tubes by a NaK secondary fluid on the shell side. The composition of the NaK secondary coolant is 67 weight percent potassium and 33 weight percent sodium. The NaK on the shell flows through a standard cruciform type radiator rejecting the waste heat to space and then returning to the condenser. Both the primary potassium and secondary NaK flows are driven by sets of parallel centrifugal pumps. This is a qualitative outline of the performance of the NEPTUNE power conversion and waste heat rejection systems. The remainder of this chapter is devoted to the description of the thermal performance of individual system components.

CORE

The nuclear reactor power was specified as 20MWt at the outset of the design in order to provide the approximate electrical power necessary for habitation support and operation of the propulsion system at all times. Additionally, the core inlet and outlet temperatures were simply specified. The inlet temperature was chosen to be 780K. This selection was an attempt to bring the potassium into the core at a low enough temperature to allow some heating of a subcooled liquid coolant while still keeping the potassium temperatures at the radiator reasonably high for efficient heat rejection. The core exit condition was specified as a saturated state at 1200K and 3.86atm. This temperature was selected to keep system pressures reasonably low to increase system reliability and keep fuel centerline temperatures well below dangerous levels.

With the reactor power coolant core entrance, and coolant core exit conditions specified, the mass flow rate (m') of the potassium through the reactor is the only remaining parameter, and it can be solved for directly the following reduction of the energy equation:

$$m' = \frac{Q'}{h_o - h_i} \tag{4.1}$$

where:

Q' = reactor power per kg
ho = coolant exit enthalpy per kg
hi = coolant entrance enthalpy per kg

With this, the primary mass flow rate of the potassium coolant is known. A further analysis using the continuity equation yields the coolant velocities at the entrance and exit. The continuity equation is given as:

$$m' = \rho V A \tag{4.2}$$

where ρ is the fluid density, V is the average fluid velocity, and A is the cross sectional area for fluid flow. The resulting inlet coolant velocity is approximately 4cm/s, and the exit average velocity for the two phase mixture is 7m/s. The inlet velocity is quite low, resulting in a laminar flow condition based on a Reynold's number calculation. However, entrance disturbances such as flow through the headers and pressure tube orifices should be great enough to insure turbulent flow. This is important to maintain good convective heat transfer conditions. Alternatively, the exit velocity of the two phase mixture exiting the core is significantly higher. However, this velocity is not prohibitively high, and the 80% quality specification is acceptable. Figure 4-1 shows the thermal performance of the core as outlined here.

TURBINES

The potassium of 80% quality leaves the core and is split into two equal mass flows and sent to the pair of Ljungstrom turbines for the extraction of work. As mentioned previously, Ljungstrom turbines are ideally suited for space applications for two reasons. First, the Ljungstrom turbines are radial flow turbines that possess an equal number of equal size counter-rotating blades, and thus, set up no net rotational moment on the spacecraft. Second, Ljungstrom turbines can easily accommodate two phase mixtures with qualities as low as 60% without blade degradation. An entrance quality of 80%, therefore, presents no problems.

A mass flow rate of 5.6kg/s enters each turbine. The turbine inlet enthalpy condition is that of the core exit, and the turbine exhaust condition was simply specified. Coomes et al. have found that a satisfactory turbine exhaust pressure for a potassium working fluid it 0.1atm. Therefore, a saturated condition of 0.1atm with a corresponding temperature of 798K was chosen for the turbine exhaust of both turbines. With the mass flow rate and turbine entrance/exhaust conditions known, the work extracted from the potassium by the turbine can be determined. The isentropic potassium

quality at the turbine exhaust can be calculated to be 0.579. This yields a value for the exit enthalpy based on an isentropic approach. Assuming an isentropic turbine efficiency of 0.93, which is given by Coomes et al., the actual work extracted by each turbine is found using the following reduction of the energy equation:

$$\dot{W}_T = \eta_{TS} m'(h_i - h_{o,s}) \tag{4.3}$$

where:

W'_T = actual turbine work
η_{TS} = isentropic turbine efficiency
$h_{o,s}$ = isentropic exit enthalpy

Assuming a generator efficiency of 0.98, the resulting work extracted by each turbine is 3.05MWe, or a total work from the turbines of 6.1MWe. With this value of actual work, the actual exit enthalpy of the potassium two phase mixture can be determined and used to predict the quality of the exhausted potassium. The calculated quality of the potassium leaving each turbine is 0.599. It should be noted here that in this design, both turbines will be capable of operating at a power level of 6.1MWe. During normal conditions, both turbines will operate at 3.05MWe to supply a total of 6.1MWe. For added reliability, however, a single turbine would be able to supply the 6.1MWe should one of the turbines fail during the life of the mission. Figure 4-2 shows the thermal performance of a single turbine as discussed above.

CONDENSER

The two flows exhausted from the turbines are rejoined to form a single flow of two phase potassium that enters a counterflow heat exchanger to be condensed and subcooled to the reactor inlet temperature condition. Since the single heat exchanger is used both to condense and subcool the potassium, it was modelled as two heat exchangers in series with an equal number and size of tubes, and the two tube lengths were simply added together to form the single heat exchanger employed.

The condenser inlet is at essentially the same state as that of the turbine exhaust, while the condenser outlet must be specified to be at a temperature of 780K (the reactor inlet temperature). Using the heat exchanger effectiveness method and specifying an effectiveness (η_x) of 0.9, the following equation is applicable to that portion of the heat exchanger responsible for condensing the potassium:

$$\eta_x = 1 - \exp\left\{\frac{UA}{(m'c_p)_{min}}\right\} \tag{4.4}$$

where:

U = overall heat transfer coefficient
A = total heat transfer area
c_p = specific heat of the shell side fluid

The overall heat transfer coefficient for a configuration such as this was taken to be 435w/m^2-K from the experimental work of Sawochka. Thus by specifying the geometry of an individual tube, equation (4.4) can be used to calculate the required number of tubes. Each tube was assigned an outer diameter of 1.0cm and a length of 3m, and the number of required tubes was calculated to be approximately 15500.

The total amount of heat that must be transferred from the potassium to the secondary NaK (Q'_{rej}) is 6.1MW less than 20MW, or simply 13.9MWt. Therefore, the temperature rise of the NaK can be found by specifying the mass flow rate of the NaK and using the following relationship:

$$\dot{Q}_{rej} = m' c_{p,NaK} \Delta T_{NaK} \qquad (4.5)$$

If the mass flow rate of the NaK is specified to be 295kg/s, corresponding to a velocity of approximately 12m/s by application of equation (4.2), and the NaK outlet temperature to be 750K, the inlet temperature of the NaK necessary to fully condense the potassium is found to be 700.5K The inlet temperature of the NaK required to further cool the potassium to the reactor inlet condition and carry away the 13.9MW of thermal energy for the given condenser geometry is 699.95K. It can be seen by comparing the inlet temperature required simply to condense the potassium and the inlet temperature required to condense and subcool the potassium that the length of additional tubing required for subcooling the liquid potassium is extremely small, and has been neglected. Thus, the final condenser geometry consists of 15500 tubes that are 3m long and have an outer diameter of 1cm. Figure 4-3 shows the thermal performance of the condenser as outlined here.

RADIATOR

The waste heat to be rejected by the radiator is 13.9MWt as has been discussed earlier. By applying the Stefan-Boltzmann relationship, the necessary radiator area can be determined. This relationship is given by:

$$E = \varepsilon \sigma A (T_{rad}^4 - T_{space}^4) \qquad (4.6)$$

where:
E = energy to be radiated
ε = emissivity of the radiator surface
σ = Stefan-Boltzmann constant
T_{rad} = average radiator temperature
T_s = ambient temperature of space

By using a calcium titanate coating on the surface of the Ti-6% Al-4% V radiator alloy, the emissivity is raised to 0.89 according to research by Jedruch. By assuming the average radiator temperature to be 725K and the ambient space temperature to be 3K, the required area was calculated to be 1009 m^2.

To determine the number of tubes required, it was necessary to specify a liquid flow rate in the radiator tubes. This value was set at 1m/s. Thus with a total mass flow rate of 295kg/s, the flow area was calculated from equation (4.2). The number of tubes was then determined by varying the tube diameter. For a diameter of 2.5cm, the number of tubes is 786. This was deemed satisfactory. The length of the tubes was then calculated by assuming that the fin width was equal to one tube diameter, and calculating the total surface area associated with this configuration as a function of length. Since the required area was known, the only unknown was the tube length. This value was calculated to be 10m. It was decided to arrange the radiator in four panels of equal size arranged in a cruciform around the boom behind the power conversion equipment. The panel width was calculated based on the total number of tubes, the diameter of the individual tubes, and the length associated with each. The width of the panels determined in this manner was 10m. Figure 4-4 shows the arrangement and dimensions of a single tube and connecting fins.

To determine the necessary tube thickness, the force placed on the wall by the moving fluid was calculated by multiplying the mass flow rate in each tube by the velocity of the fluid (1m/s). By applying the following equation, the inner tube radius was determined:

$$\frac{F}{\sigma} = \pi(r_o^2 - r_i^2) \qquad (4.7)$$

where σ represents the stress on the tube wall. Using equation (4.7), it was determined that for a wall thickness of 0.1cm, the applied stress was approximately 150MPa. This provides a factor of safety of about 3 below the yield stress of the radiator alloy at 800K (414MPa) as reported by Jedruch. The mass of the radiator was calculated based on the thickness just determined, and the area of the entire device. The volume represented by the radiator is 1 million cubic centimeters. Multiplying this value by the density of the radiator alloy (6g/cc), the mass was calculated to be 6000kg.

The reason that fin effectiveness was not used for the analysis of the radiator was the fact that that particular method is based on convective cooling of the fins. Since there can be no convection is a system such as a space radiator, these procedures are invalid. Thus, the radiator parameters were calculated completely on the basis of the area required as determined from equation (4.6). For a schematic of the cruciform radiator configuration, refer to figure 4-5.

PUMPS

The coolant flows on both the primary potassium loop and the secondary NaK loop are driven by centrifugal type pumps in a parallel arrangement as shown in figure 1-2. This parallel arrangement reduces the amount of work required by an individual pump, thus lessening its chance of failure. Thus, each pump receives only half of the total mass flow rate for the loop. Should one of the pumps fail on either loop, the flow could be maintained at half of the design flow rate by the remaining pump. While this situation is not particularly attractive, the failure of a single pump will not cripple the NEPTUNE system.

The pressure rise provided by the pumps is obtained by summing the pressure drops around the particular loops. For the primary loop, the pressure drop across the turbine is specified. The pressure drop through the condenser is negligible. The pressure drop through the core was taken from experimental data of Peterson for a similar configuration with boiling potassium. Knowing the pressure rise the pump needs to provide, the pump work can be determined using the following relationship:

$$W_p' = \frac{m' v \Delta P}{\eta_{PS}} \tag{4.8}$$

where:

W'_p = actual pump work (both pumps)
v = specific volume of the working fluid
ΔP = pressure drop around loop
η_{PS} = isentropic pump efficiency

An isentropic pump efficiency of 0.9 was used for all pumps. Using equation (4.8), the total pump work required to drive the primary loop potassium is 9.03kWe.

For the secondary loop, the only significant pressure drop is that through the radiator. In order to obtain a reasonable estimate of the radiator pressure drop, the mechanical energy equation with frictional losses was employed:

$$\frac{P_1 - P_2}{\rho} + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2) + f\frac{L V_1^2}{D2} = 0 \tag{4.9}$$

where:

P = pressure at inlet/outlet
V = velocity at inlet/outlet
g = gravitational acceleration
z = elevation at inlet/outlet
f = friction factor
L = radiator tube length
D = radiator tube diameter

The change in velocity is zero since there is no cross sectional area change and the flow is steady

state. Gravitational acceleration is zero in the spacecraft environment. The Reynold's number of the secondary flow was found to be 164. Since this is in the laminar flow regime, the friction factor was found as 64/Re. The resulting pressure drop through the radiator was calculated to be 1.19atm, requiring a total secondary pump work of 53.98kWe. Figure 4-6 shows the thermal performance of both a primary and secondary pump.

ACCUMULATORS

It is probable that the system will be launched with both the primary and secondary coolants frozen in solid form. This is necessitated by the fact that the melting points of both potassium and NaK are well above ambient launch conditions. Once in space, the coolants will be melted either by the reactor or external heaters. Therefore, accumulators will be required to take in excess liquid volume due to thermal expansion. As can be seen from figure 1-2, the system accumulators are located on the primary loop at the high pressure side of the main and secondary coolant pumps. This is to insure that initial coolant thermal expansion can be accommodated. Since the accumulators are located at the high pressure sides of the pumps, no backflow will be permitted. The accumulators do not act as system pressurizers during normal operation of the system. Their principle function is to accommodate coolant thermal expansion during the initial thaw as well as during unexpected temperature transients. System pressurization is maintained by the boiling interface in the reactor core.

An alternate accumulator scheme would be one in which the accumulators are connected to the hot leg of the reactor. At this location, however, the accumulator would be required to accommodate a two phase mixture. This could be done only by centrifugal forced induced by component rotation. This type of system seems more complex than the system outlined above, and was not considered for implementation in the NEPTUNE system.

SUMMARY

The overall system efficiency is given by the following equation:

$$\eta = \frac{W_{net}}{Q_{in}} = \frac{\dot{W}_{turbine} - \dot{W}_{pri\ pump} - \dot{W}_{sec\ pump}}{\dot{Q}_{reactor}} \qquad (4.10)$$

Evaluating this expression with the component values that have been determined in the sections above yields an overall system efficiency of 30.18%. A summary of the important system parameters specified and calculated in this chapter can be found in table 4-1.

REFERENCES

1. Coomes, E.P., Johnson, B.M., Bomelburg, H.J., "A Combined Rankine/Brayton Pulsed Power Cycle," 5th Symposium for Space Nuclear Power Systems, Albuquerque, NM, 1988.

2. Ewing, C.T., et al., "High Temperature Properties of Potassium," NRL-6233, 1965.

3. Fox, R.W., McDonald, A.T., Introduction to Fluid Mechanics, John Wiley & Sons, New York, 1985.

4. Handbook of Chemistry and Physics, 68th edition, CRC Press, Boca Raton, FL, 1987.

5. Incropera, F.P., DeWitt, D.P. Fundamentals of Heat and Mass Transfer, John Wiley & Sons, New York, 1981.

6. Jedruch, J., "A Multimegawatt Space Power Source Radiator Design," 5th Symposium for Space Nuclear Power Systems, Albuquerque, NM, 1988.

7. Rust, J.H., Nuclear Power Plant Engineering, S.W. Holland Co., Atlanta, GA, 1979.

8. Sawochka, S.G. "Thermal and Hydraulic Performance of Potassium During Condensation Inside Single Tubes," NASA CR-851, 1967.

9. Wark, K., Thermodynamics, McGraw-Hill Book Co., New York, 1983.

Table 4-1: NEPTUNE system parameters

CORE:

Thermal Power	20 MWt
Inlet Temperature	780K
Inlet Pressure	5.36 atm
Outlet Temperature	1200 K
Outlet Pressure	3.86 atm
Exit Quality	80%
Mass Flow Rate	11.1 kg/s

TURBINE:

Inlet Temperature	1200 K
Inlet Pressure	3.86 atm
Inlet Quality	80%
Outlet Temperature	798 K
Outlet Pressure	0.1 atm
Exit Quality	59.90%
Electric Power	6.1 MWe
Mass Flow Rate (each turbine)	5.55 kg/s

CONDENSER:

Primary Inlet Temperature	798 K
Primary Inlet Quality	59.90%
Primary Outlet Temperature	780 K
Primary Pressure	0.1 atm
Primary Mass Flow Rate	11.1 kg/s
Secondary Inlet Temperature	700 K
Secondary Outlet Temperature	750 K
Secondary Mass Flow Rate	295 kg/s

RADIATOR:

Number of Tubes	786
Tube Diameter	2.5 cm
Cruciform Blade Length	10 m
Cruciform Blade Width	10 m
Total Radiative Surface Area	1009 m^2
Average Radiator Surface Temperature	725 K
Waste Heat Rejected	13.9 MWt
Radiator Mass	6000 kg

PUMPS:

Total Primary Pump Work	9.03 kWe
Primary Pressure Rise	5.26 atm
Total Secondary Pump Work	53.98 kWe
Secondary Pressure Rise	1.19 atm

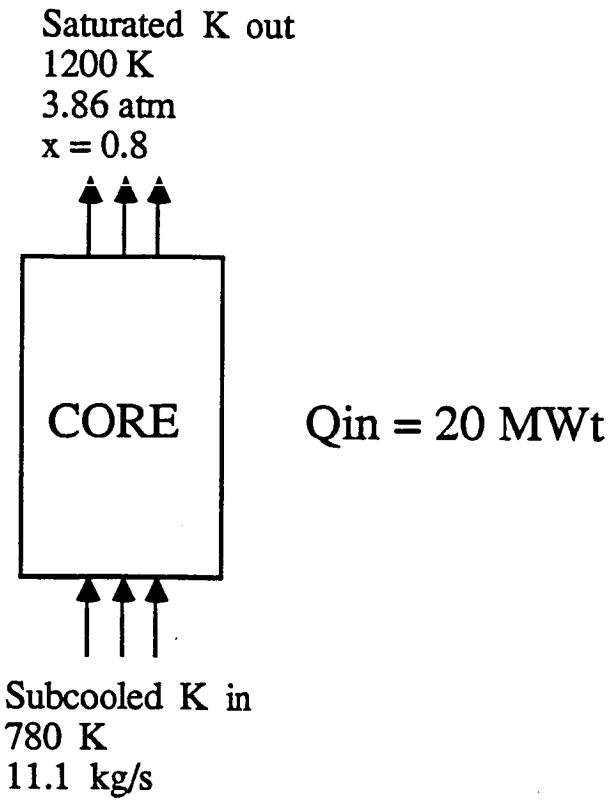


Figure 4-1. Core Thermal Performance.

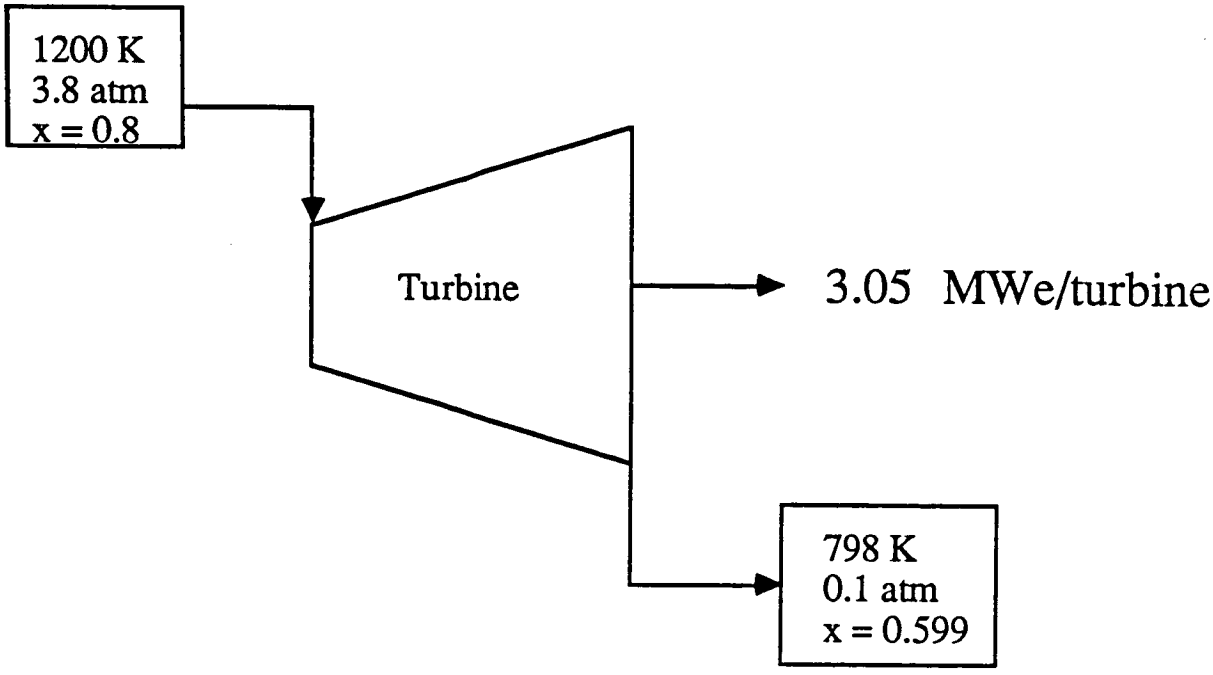


Figure 4-2. Turbine Thermal Performance.

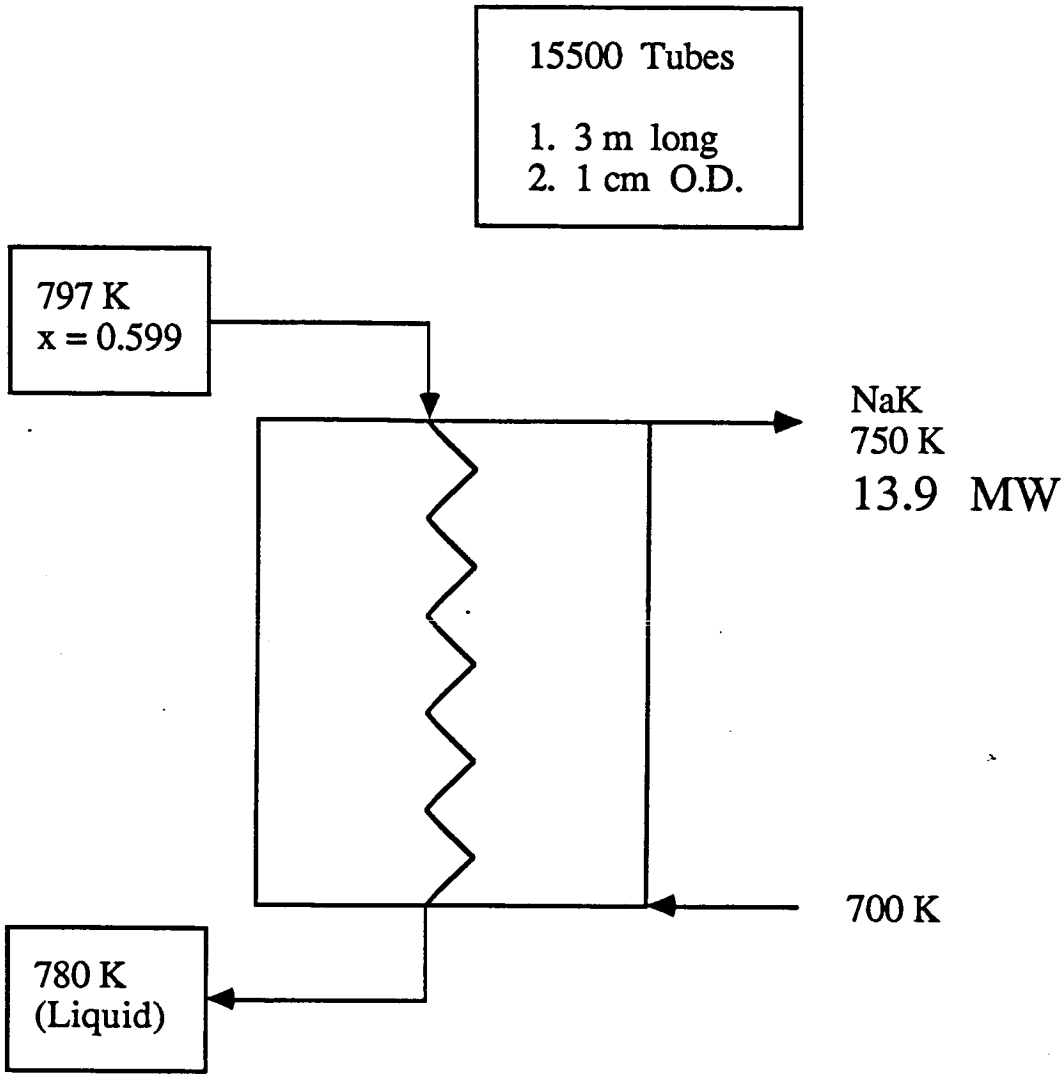


Figure 4-3. Condenser Thermal Performance.

"Tube & Fin Type Radiator"
Area = 1009 sq. meters

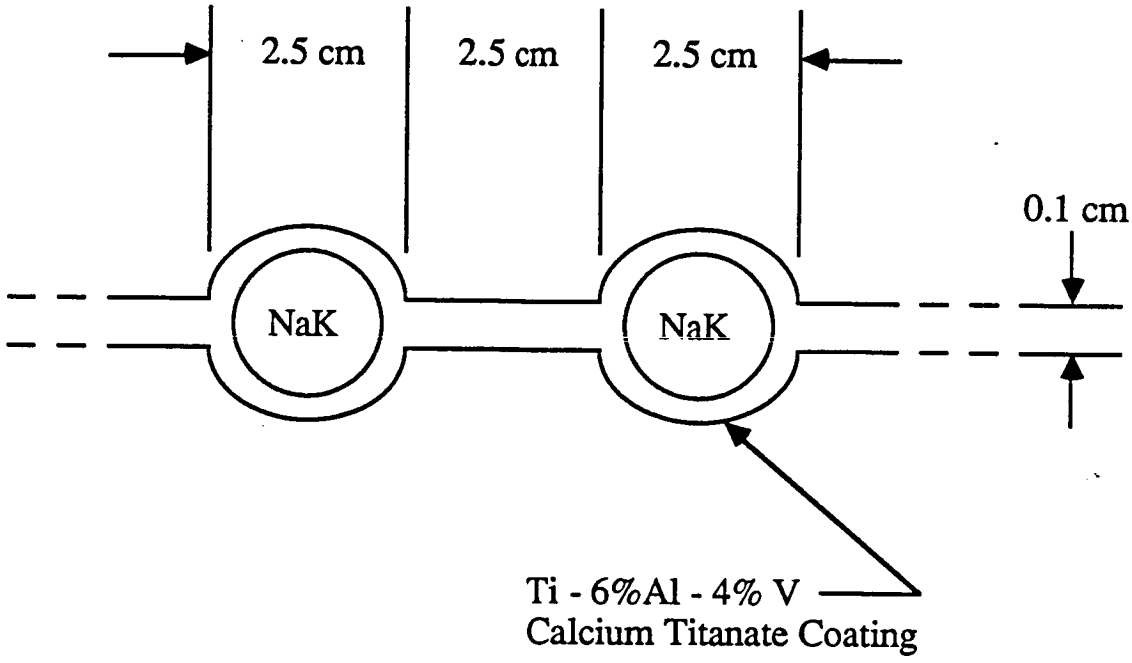


Figure 4-4. Radiator Tube & Fin Arrangement.

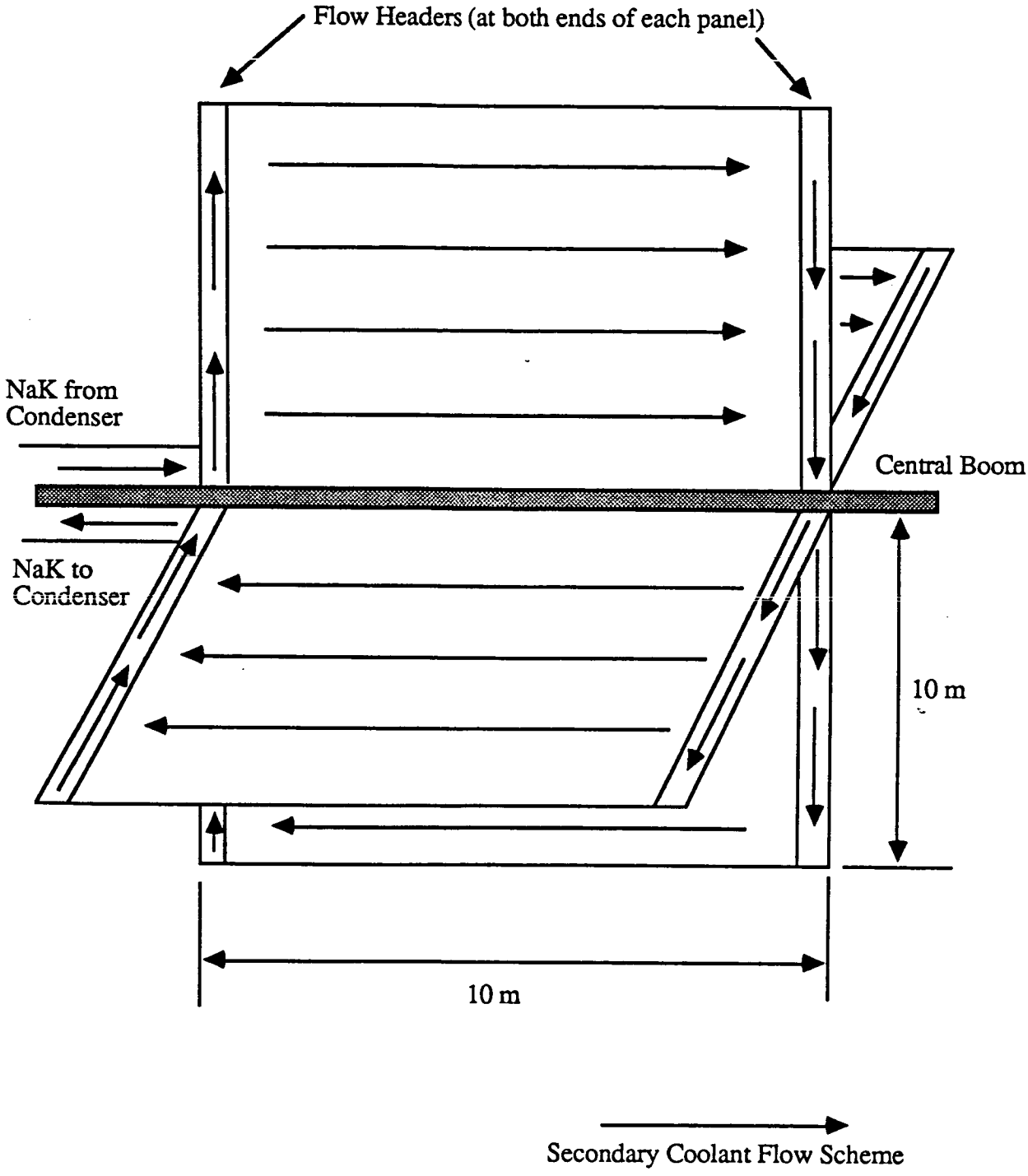


Figure 4-5 - Cruciform Radiator Configuration and NaK Flow Scheme

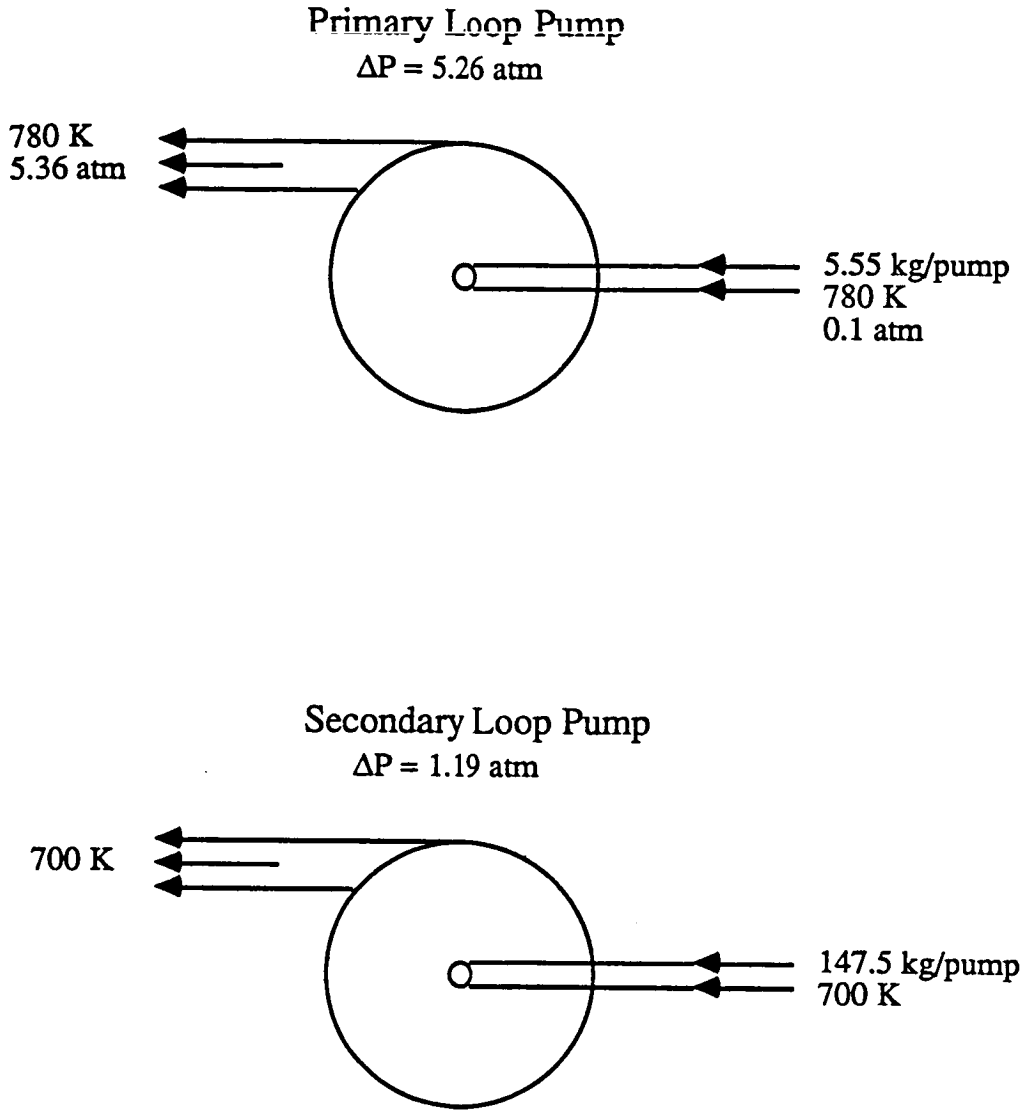


Figure 4-6. Primary and Secondary Loop Pump Thermal Performance.

CHAPTER FIVE: PROPULSION

THRUSTER SELECTION

For space missions to the outer planets, it is desirable to utilize non-chemical propulsion systems in order to decrease the required propellant mass which must be carried. In order to compare systems in this respect, the parameter of specific impulse (I_{sp}) is defined:

$$I_{sp} = \frac{v_{ex}}{g} \tag{5.1}$$

where:

I_{sp}	=	specific impulse
v_{ex}	=	exhaust velocity of the propellant
g	=	gravitational acceleration constant ($9.8 m/s^2$)

Other parameter used to compare thruster performance include thruster efficiency and power/thrust ratio.

There exist four areas of non-chemical propulsion: electrically powered propulsion devices, direct nuclear propulsion, sail designs, and applications of laser technologies. For manned missions, sail designs must be eliminated due to the extremely low thrust levels and consequently large transit times. Laser powered propulsion systems include laser thermal propulsion and the laser sail. Laser thermal propulsion consists of beaming a laser from Earth, focusing it into a heating chamber where it is absorbed by the propellant which is then expelled at high velocities. By heating the propellant with a laser, there is no inherent limit to temperatures which can be obtained. In this manner, specific impulses on the order of 1000 seconds may be obtained, and perhaps more depending upon the operating temperature. A thrust as large as 1000N could be obtained with a supply of a 10MW laser and a mass flow rate of 0.1kg/s of propellant. However, for a mission to the outer planets, this is much too great of a mass flow rate. Also, laser thermal propulsion has not yet been extensively developed. Consequently, it must be eliminated as an alternative at this time. The laser sail operates in a similar manner as the solar sail, but instead of being propelled by radiation from the sun, it is propelled by beamed microwaves. This allows much greater thrust levels and a greater degree of control. The laser sail is a promising alternative for future long range space missions, but at present, not enough research and testing has been performed to make the laser sail a viable option.

Direct nuclear propulsion has the advantage supplying high thrust levels, but only possess a

specific impulse on the order of 850 seconds. Coupled with the fact that a reactor with a power level of 1100MWt is required (based on the NERVA system), this system is undesirable. Other designs exist which employ smaller, particle-bed reactors. These possess lower thrust levels, on the order of 200N, but still possess low specific impulses (1000-1500 seconds) which make them poor choices for outer planet missions.

The remaining alternatives to non-chemical propulsion include various electrically powered devices. The first of these is the electrochemical thruster, which can be either an arcjet or resistojet. The arcjet produces thrust by heating the working fluid with an electric arc and then expelling it through a nozzle. The arcjet is severely limited in that the maximum possible overall efficiency is only 30- to 40% because of electrically induced ionization in the propellant. Also, the arcjet possesses a specific impulse of about 1200 seconds, significantly lower than other, more efficient alternatives. The resistojet produces thrust by heating the propellant through resistively heated walls. This allows an efficiency of about 88% to be obtained, but still only yields a specific impulse of 1000 seconds.

The next electrically powered thruster is the pulsed plasma thruster. The oldest design of this type is the rail gun which accelerates plasma along rails through the use of a discharging capacitor. This method can yield thrust levels up to 1000N, but consumes large amounts of power. For one thruster, 12.5MWe is required when the thruster operates at its maximum efficiency of 40%. A newer design for a pulsed plasma thruster is the magnetoplasmadynamic (MPD) thruster. In the MPD, propellant is injected, ionized by a high-current discharge, and then a magnetic field generated by a large current is used to accelerate the propellant. The MPD can produce about 100N of thrust a a specific impulse of 2500 seconds and a power of 25 kWe. However, the efficiency of the MPD is low with about 34% being obtained.

The final type of electrically powered propulsion is electrostatic propulsion. Electrostatic propulsion operates by ionizing the propellant and then accelerating it through an electromagnetic field to be expelled at high velocities, where it is remixed with electrons. The ionization of the working fluid can be achieved in two ways. The first is through contact of a working fluid possessing low ionization potential with a heated material that has a high work function. In this manner, 99% of the working fluid may be ionized, but radiative power losses occur in the ionizing element, which consequently reduces the overall efficiency. A superior method for ionizing the working fluid is by bombarding it with electrons which are accelerated through a potential difference. This technique also ionized greater than 90% of the working fluid, but has no radiative losses. Electrostatic thrusters in general can obtain specific impulses up to 10,000 seconds and the electron bombardment thruster possesses an efficiency of 70%, making it the superior choice for utilization in missions to the outer planets. Figure 5-1 and Table 5-1 display the characteristics of

the various types of thrusters.

The choice is obviously between the JPL/Hughes thruster and the final NASA-Lewis thruster. The two are essentially equivalent in performance. The only difference is the fact that a system composed of NASA-Lewis thrusters would be composed of fewer units. Consequently, a unit failure when utilizing these thrusters would be a much greater proportionate loss than one in a system employing the JPL/Hughes (J-series) thrusters. For this reason, the JPL/Hughes model was selected for use in the NEPTUNE system. Figure 5-2 shows a detailed sketch of the thruster selected for the mission.

PROPELLANT CALCULATIONS

The propellant required for the propulsion system depends upon the thrust level and specific impulse. With 5.50MWe available for propulsion in the NEPTUNE system, 240 J-series thrusters may be employed at a time. This yields a thrust level of 88.8N, from the data given in Table 5-1. The mass flow rate is given by the equation:

$$m' = \left(\frac{T}{I_{sp}}\right)/9.80 \qquad (5.2)$$

where T is the thrust. Substituting in the calculated thrust level and a specific impulse of 9000 seconds, the mass flow rate is calculated to be 0.001kg/s. Allowing for seven years of continuous firing, the total propellant mass required is found to be 221,000kg. The seven year thrust time was determined from a simple orbital transfer calculate for the reference mission to Jupiter.

The total mass of the thrusters depends only upon the number carried. For electron bombardment thruster, the lifetime is limited due to screen grid erosion. At present, the screen grid lifetime for the J-series thruster is approximately 15,000 hours. Once again using a continuous firing time of 7 years, this necessitates a multiplication factor of four. In order to add a margin of safety, a total of 1000 thrusters were decided on which gives a total mass for the thruster of 245,780kg. Consequently, the total propulsion system mass is the propellant plus the thrusters, yielding a mass of 466,780kg. The propulsion system characteristics are summarized in Table 5-2.

There are some hazards associated with the release of mercury into the environment. Mercury is a very toxic substance that would cause great damage to the ecology of any system into which it was introduced in large amounts. Since the 221,000kg of mercury to be used as propellant in the NEPTUNE system must be launched into orbit (presumably by a yet-to-be-built heavy launch vehicle) precautions must be taken to avoid the accidental release of the mercury into the environment. Thus, in the case of a launch failure, there would be little threat to the well being of the environment.

REFERENCES

1. Barber, J.P., "Electric Rail Gun Application to Space Propulsion", Progress in Astronautics and Aeronautics, v79, pp. 641-51, 1981.

2. Kaplan, M.H., Trn, R.M., Buden, D., "Nuclear Electric Orbital Transfer Vehicle for the Shuttle Era", Progress in Astronautics and Aeronautics, v79, pp. 59-70, 1981.

3. Katz, E.L., "Electric Propulsion", AIAA Short Lecture Series, Los Angeles Section for Monographs: Advanced Propulsion Systems for Space Application, v1, M. Wong, ed., pp.46-69, 1965.

4. Keeter, D., et al, "Laser Thermal Propulsion", Progress in Astronautics and Aeronautics, v89, pp. 129-48, 1984.

5. Kemp, N.H., Legner, H.H., "Steady (Continuous Wave) Laser Propulsion Research Areas", Progress in Astronautics and Aeronautics, v89, pp.109-27, 1984.

6. Seikel, G.R., York, T.M., Condit, W.C., "Applied-Field Magnetoplasmadynamic Thrusters for Orbit-Raising Missions", Progress in Astronautics and Aeronautics, v79, pp. 59-70, 1981.

Table 5-1 - Thruster Comparisons

Type	Thrust (N)	Isp (s)	Efficiency (%)	Power Required (kWe)	Power/Thrust (kWe/N)	Specific Mass (kg/kWe)	Total Mass (kg)
NASA-Lewis	0.129	2900	67	3.06	23.72	16.78	51.36
JPL/Hughes	0.37	9000	80	22.68	61.3	10.84	245.78
NASA-Lewis	0.5	9000	80	30.65	61.3	10.61	325.46

Table 5-2 - NEPTUNE Propulsion System Characteristics

Type	JPL/Hughes J-Series
Size	30-cm screen grid
Working Fluid	Mercury
Total Number of Thrusters	1000
Thrusters Firing at Once	240
Total Constant Thrust	88.8 N
Power Required	5.50 MWe
Propellant Mass	221,000 kg
Thruster System Mass	245,780 kg
Total System Mass	466,780 kg

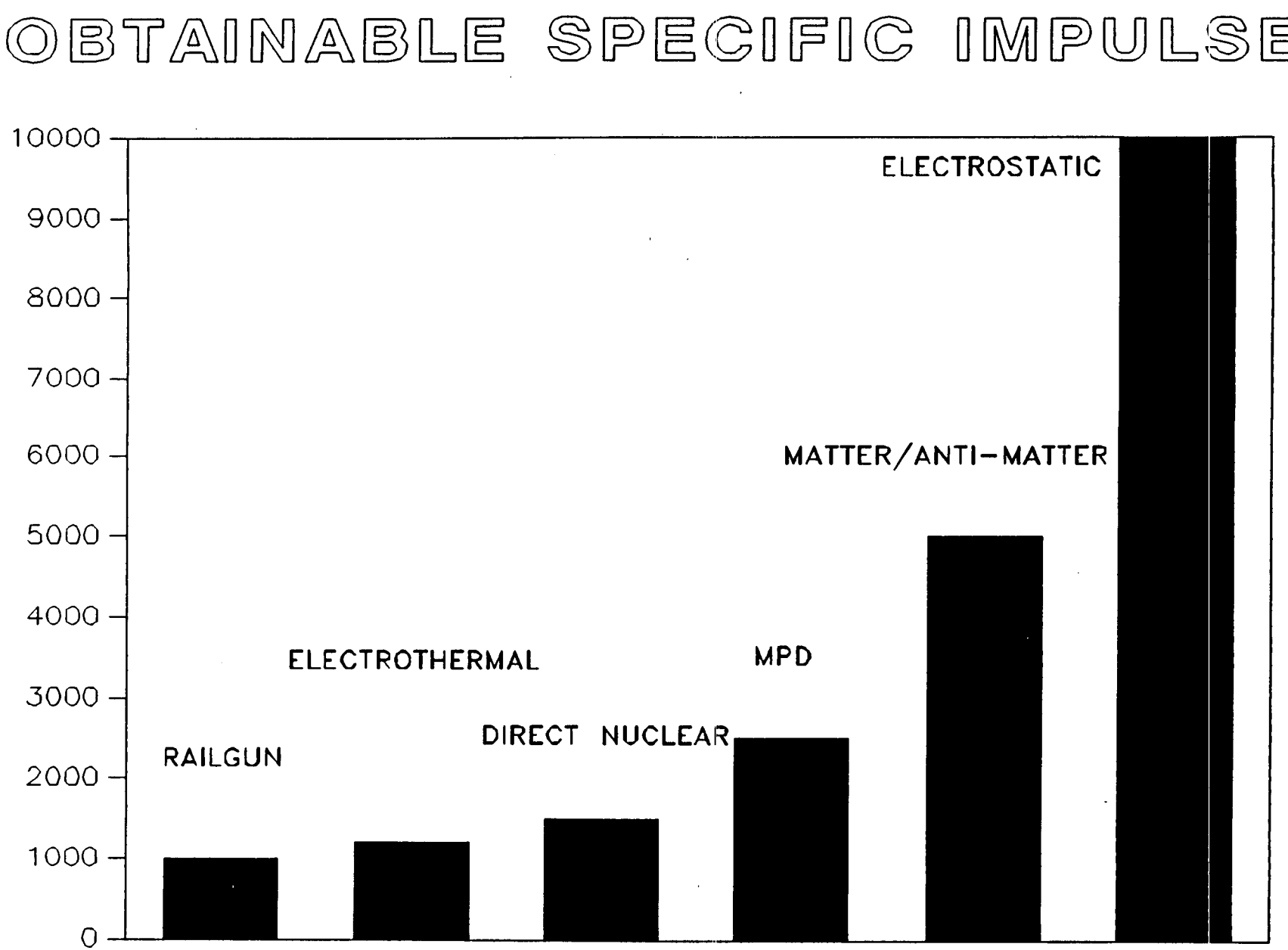


Figure 5-1 - Comparison of Specific Impulse

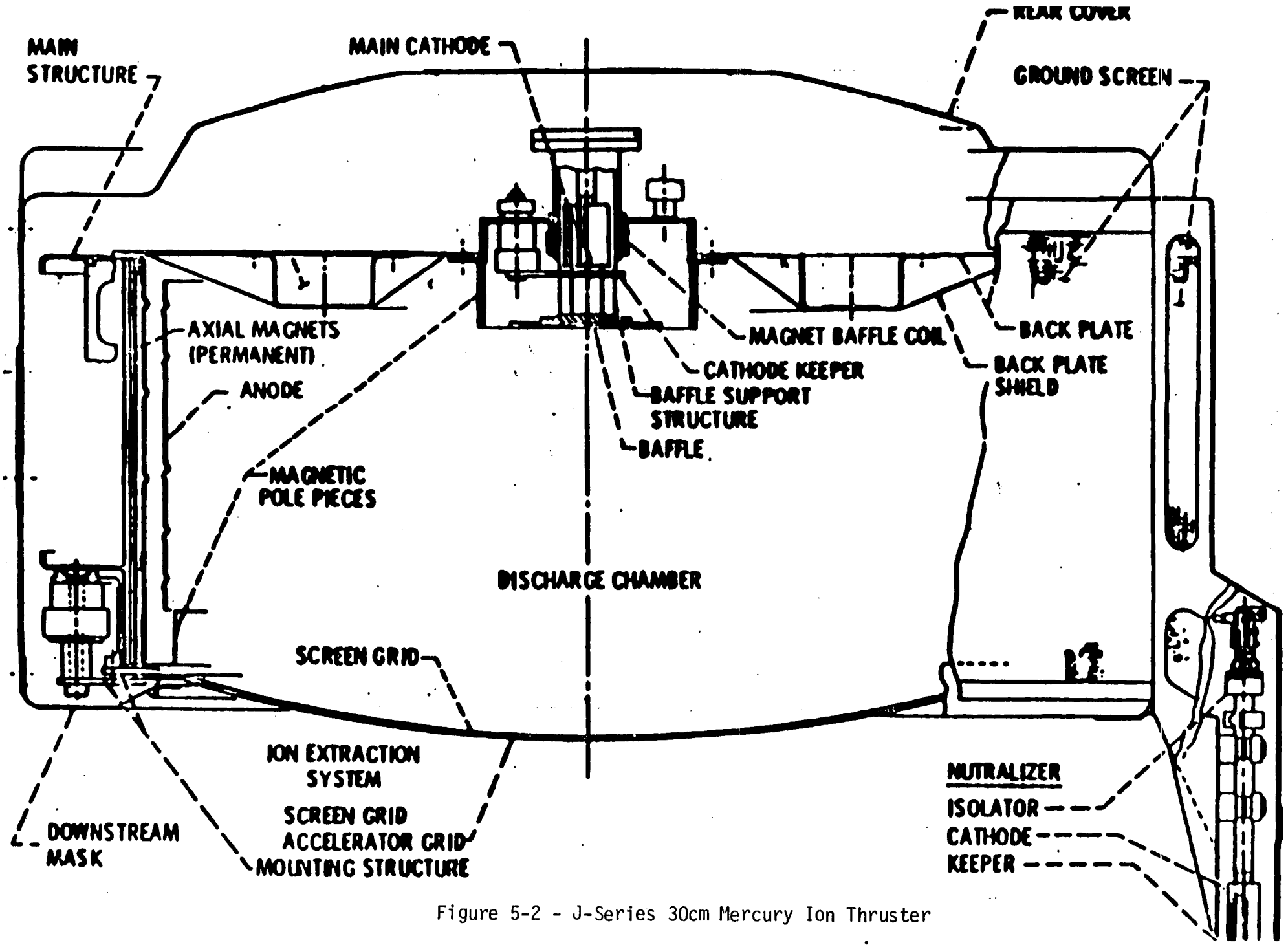


Figure 5-2 - J-Series 30cm Mercury Ion Thruster

CHAPTER SIX: SHIELDING

This chapter will deal only with shielding of the payload and secondary system from radiation emitted from the reactor core. This section will not cover shielding required to protect against cosmic radiation. The shielding mass needed to attenuate cosmic radiation was taken into consideration when the payload mass was evaluated in Chapter 2.

The maximum allowable dose rate due to neutrons and gammas at the payload was set at 0.1 rad/week or 5.0 rem/yr. The shielding thicknesses and boom lengths were optimized by using the DOSE_4_NEPTUNE code to achieve the required dose rate. A copy of the code listing is available in Appendix One.

SHADOW SHIELDING

The shadow shielding concept is used in most space applications of nuclear power systems where instrumentation or men must be protected from the harmful affects of radiation. Shielding and distance are the two most important factors in reducing dose to equipment and people.

Figure 6-1 shows how shadow shielding and distance are both employed by the NEPTUNE configuration to reduce dose to the secondary system and payload. A tungsten (W) and lithium hydride (LiH) shielding configuration is placed between the secondary system and the payload. By using the known radius of the secondary system, the radius and length of the core, and the distances that separate the core from the shielding and the shielding from the secondary; the radii of the frustum-shaped shielding was able to be calculated from geometrical manipulations.

Although the payload is placed far from the shielding, the secondary system is placed 1.0 m behind the LiH shield. The secondary system is placed as near the reactor as possible, yet it needs to be shielded from the large amounts of radiation coming from the core. The secondary system needs to be shielded to reduce the adverse material effects caused by high levels radiation. Since the ship is manned, the payload is placed a much farther distance away because doses to the payload had to be minimized. Also, the tank holding the mercury propellant is placed between the secondary system and the payload to further reduce the dose at the payload due to gammas.

NEUTRON SHIELDING

For the neutron shielding, LiH is employed. LiH is used because of its favorable cross section values and its relatively light weight. The LiH will likely be surrounded by a stainless steel

shield to help maintain the LiH shielding in case of melting, swelling, cracking, or thermal dissociation of the LiH. Li-7 enriched lithium hydride shielding is used to minimize the internal heating within the shield. Li-6 absorbs a thermal neutron to produce a tritium nucleus and an alpha particle. The Li-7 reacts with fast neutrons but has a smaller thermal neutron cross section. Figure 6-2 shows the neutron absorption cross sections for Li-6 and Li-7 as a function of neutron energy.

LiH shielding must be maintained in relatively narrow temperature range, and this is probably its greatest disadvantage. The optimal operating temperature range is between 600 to 680 K. Since radiolytically dissociated LiH does recombine efficiently at temperatures below 600 K, significant swelling could occur in the LiH shielding if the temperature drops below 600 K. 680 K is also well below the melting point of lithium (960 K), and the temperature at which thermal dissociation of LiH could result in hydrogen loss if the shield were punctured.

LiH also does not attenuate gammas well, so it must be used in conjunction with another material that is a good gamma-attenuating material.

GAMMA SHIELDING

In the NEPTUNE shielding configuration, tungsten (W) is used to attenuate gammas. It was chosen because of its high gamma attenuation and good structural properties. The W shielding is placed nearer to the core than the LiH. The tungsten is denser than the LiH, thus for weight considerations it is placed where its volume will be least. Also, the tungsten reflects some fast neutrons, so placing it before the LiH will reduce neutron flux to the LiH shield. Thirdly, the tungsten will act as part of a needed thermal barrier between the core and the LiH.

The tank holding the mercury propellant was also placed between the shielding and the payload to further attenuate gammas.

DOSE CALCULATIONS

The ANISN code was employed to evaluate the fraction of neutrons and gammas that made it through the shielding. This was accomplished by identifying the shielding as one node with 200 meshes; simulating a one dimensional slab geometry. A uniform flux was placed on the right hand side and from the output, the fraction of escaping gammas and neutrons could be determined. Table 6-1 shows these values for various shielding thicknesses.

Table 6-1 Fraction of Escaping Neutrons and Gammas From the LiH Shielding

LiH Thickness (cm)	Fraction of Neutrons	Fraction of Gammas
150	2.72E-4	0.447
180	6.55E-5	0.391
200	2.54E-5	0.357
220	9.91E-6	0.325

The shielding dimensions were determined with the following equations (refer to Figure 6-3):

$$i = \arctan\left\{\frac{\left(\frac{d}{2}-\frac{c}{2}\right)}{\left(C + T_W + T_{LiH} + DCS + DSS\right)}\right\} \tag{6.1}$$

$$W_{\text{inner radius}} = \left(c + DCS\right)\tan(i) + \frac{c}{2} \tag{6.2}$$

$$W_{\text{outer radius}} = \left(c + DCS + T_W\right)\tan(i) + \frac{c}{2} \tag{6.3}$$

$$LiH_{\text{inner radius}} = W_{\text{outer radius}} \tag{6.4}$$

$$LiH_{\text{outer radius}} = \left(c + DCS + T_W + T_{LiH}\right)\tan(i) + \frac{c}{2} \tag{6.5}$$

where:

T_W	=	thickness of tungsten
T_{LiH}	=	thickness of lithium hydride
c	=	length of the core
d	=	diameter of secondary system
DCS	=	distance from core to secondary system
DSS	=	distance from shielding to secondary system

Table 6-2 shows the results of using equations (6.1) through (6.5) to determine shielding

dimensions.

Table 6-2 Calculated Radii of the Shielding

The distance from the core to the shielding = 100 cm
The distance from the shielding to the secondary = 100 cm
The core length = 120 cm
(the core length is increased slightly to be conservative)

Shielding Thickness (cm)	* 1st Shielding Radius (cm)	* 2nd Shielding Radius (cm)
183.5	143	212
203.5	140	214
223.5	137	215

*These values were calculated using the DOSE_4_NEPTUNE code shown in Appendix I.

Assuming an isotropic point source at the center of the reactor, the fraction of core flux that actually entered the shielding was evaluated.

$$f = \frac{\pi(W_{inner})^2}{4\pi\left(\frac{c}{2} + DCS\right)^2} \tag{6.6}$$

where:

f = the fraction of the reactor flux that enters the shielding
W_{inner} = inner radius of the tungsten shielding

The neutron flux exiting the shielding was determined by:

$$\Phi_e = fn\Phi_{core} \tag{6.7}$$

where:

Φ_e = flux passing through the shield
Φ_c = core neutron flux
n = fraction of neutrons that escape the LiH shielding
f = fraction of reactor flux entering the shielding

Paraffin of only 35 cm thickness will thermalize the majority of neutrons that pass through

it, and LiH is a better moderator than paraffin. Thus, at the thicknesses this work considers (> 150 cm), all the escaping neutrons from the shielding can be considered thermal. The neutron flux decreases inversely with the square of the distance, so the neutron flux at the payload is determined by:

$$\Phi_p = \frac{\Phi_e}{d^2} \tag{6.8}$$

where Φ_p is the neutron flux at the payload, and d is the distance from the shielding to the payload.

The total dose due to neutrons at the closest end of the payload is evaluated by:

$$\text{Dose Rate} = TC\Phi_p \tag{6.9}$$

where:

T	=	seconds/year conversion factor (3.1536E+07 s/yr)
C	=	thermal neutron fluence to dose conversion factor (2.8E-11 n/cm^2)

The attenuation of gammas through the various shields was calculated by:

$$\Phi_\gamma = ff_\gamma \Phi_c e^{-(f\rho T_W)} \tag{6.10}$$

where:

Φ_γ	=	exiting gamma flux from shield
f	=	mass attenuation coefficient for tungsten (0.0416 cm^2/g for 6MeV gammas)
ρ	=	density of tungsten (19.3 g/cc)
f_γ	=	fraction of gammas that escape LiH shielding

The gamma rays exiting the shielding must also go through the mercury propellant before reaching the payload. Thus the gamma flux reaching the payload is:

$$\Phi_{\gamma p} = \frac{\Phi_\gamma}{d_{st}^2 d_{tp}^2} e^{-(f\rho t_t)} \tag{6.11}$$

where:

$\Phi_{\gamma p}$	=	gamma flux at payload
d_{st}	=	distance from shielding to mercury tank
d_{tp}	=	distance from mercury tank to payload
t_t	=	thickness of the mercury tank
f	=	mass attenuation coefficient for Pb (0.0435cm/g for 6 MeV gammas)
ρ	=	density of Pb

The mercury propellant was modeled as lead since data could not be found for Hg. Mercury and lead, however, share a similar density, and therefore, similar attenuation properties. The dose at the payload due to gammas was found by:

$$\text{Gamma Dose Rate} = ChE f \rho \tag{6.12}$$

where:

C = conversion factor (0.01 J/kg/rad)
h = Boltzmann's constant
E = gamma ray attenuation

The total dose then is the summation of the neutron dose and the gammas dose.

$$\text{Total Dose Rate} = \text{Neutron Dose} + \text{Gamma Dose} \tag{6.13}$$

The preceding equations were used to develop a FORTRAN code specifically for the NEPTUNE system; DOSE_4_NEPTUNE. Using the DOSE_4_NEPTUNE code, the boom length (defined as the distance between the LiH shielding and the payload) and LiH thicknesses were optimized. Results of the optimization are illustrated in Figure 6-4. It was found that at long boom lengths, dose rates due to gammas from the core were negligible at the payload. Negligible gamma dose rates at the payload also occurred when the all the mercury was removed revealing that the mercury propellant tank does not add significant protection against gamma radiation and can be moved if necessary.

After several iterations (the results of which are in Appendix One), a final shielding configuration was established which is shown in Figure 6-5. The total mass of the tungsten is 3400 kg, and the total mass of the LiH is 10300 kg. This sums up to a total shielding mass of 13700 kg. Since Figure 6-4 shows small variations in dose as a function of boom length at a shielding thickness of 220 cm, a boom of 500 m in length was decided upon. The total dose rate for these parameters is 2.4 rem/yr, offering a factor of safety of two for dose to personnel.

Table 6-3 Final Shielding Parameters

LiH thickness	220 cm
W thickness	3.5 cm
LiH mass	10300 kg
W mass	3400 kg
Total mass	13700 kg
boom length	500 m
TOTAL DOSE RATE at payload	2.4 rem/yr

REFERENCES

1. Blink, J.A., Krikorian D.H., Hoffman H.J., "The Use of Lithium in Fusion Reactors", UCRL-85145, Lawrence Livermore National Laboratory, CA, 1981.

2. Cember, H., Introduction to Health Physics, 2nd edition, Pergamon Press International , 1983.

3. "Chart of the Nuclides", 13th edition, General Electric Company, 1984.

4. El-Genk, M.S. et al, "Review of the Design Status of the SP-100 Space Nuclear Power System", 1st Symposium on Space Nuclear Power Systems, Albuquerque, NM, 1983.

5. Hoover M.D., et al, "Overview of the Hazards of Using Lithium in Space Nuclear Reactor Systems", 2nd Symposium on Space Nuclear Power Systems, Albuquerque, NM, 1984.

6. Hurst, G.S., Ritchie, R.H., eds, "Radiation Accidents: Dosimetric Aspects of Neutron and Gamma-Ray Exposures", ORNL-2740, Part A, November 1959.

7. "Radiological Health Handbook", U.S. Department of Health Education and Welfare, 1970.

8. "Radiation Protection Procedures", International Atomic Energy Agency, Vienna, 1973.

9. Welch F.H., "Lithium Hydride Technology", NAA-SR-9400, Atomics International, Canoga Park, CA, 1967.

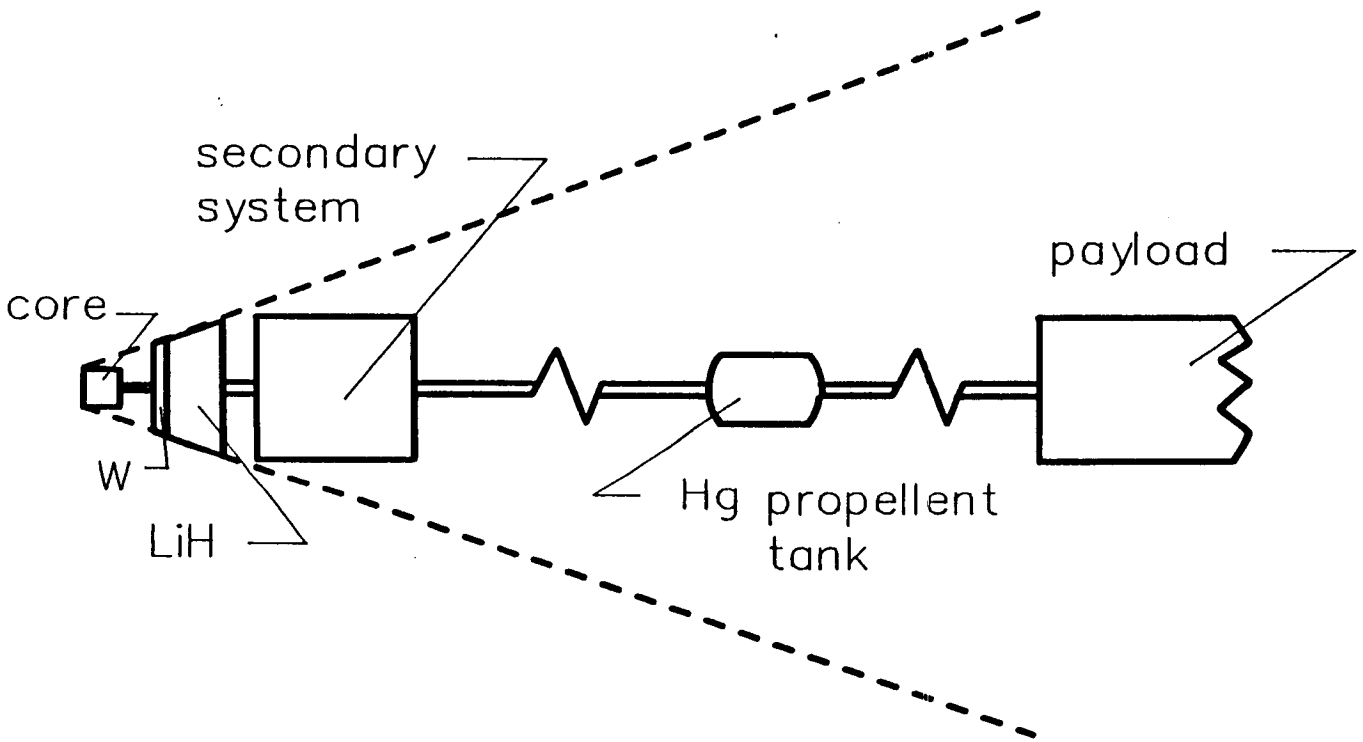


FIGURE 6-1 Shadow Shielding Diagram

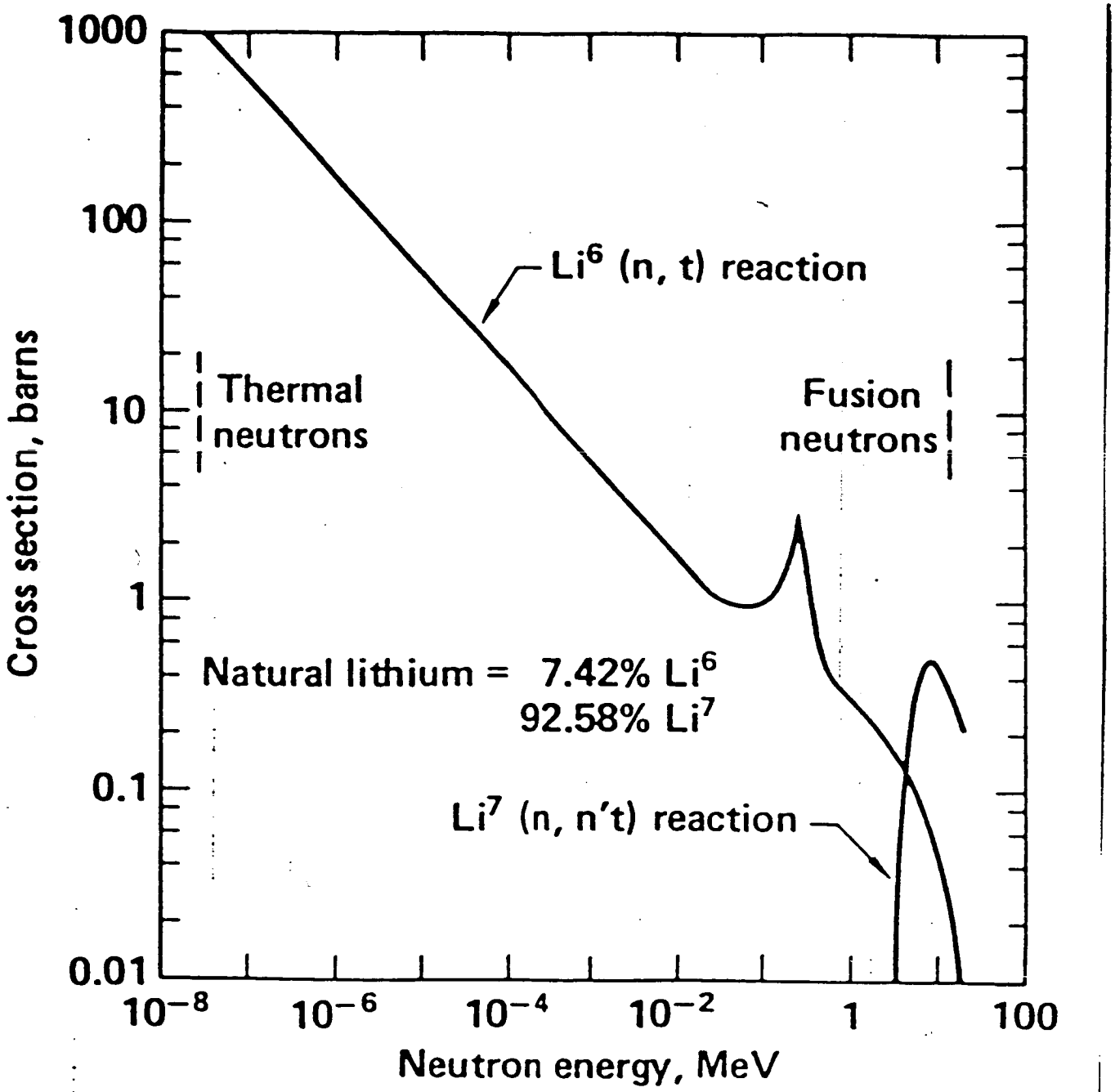
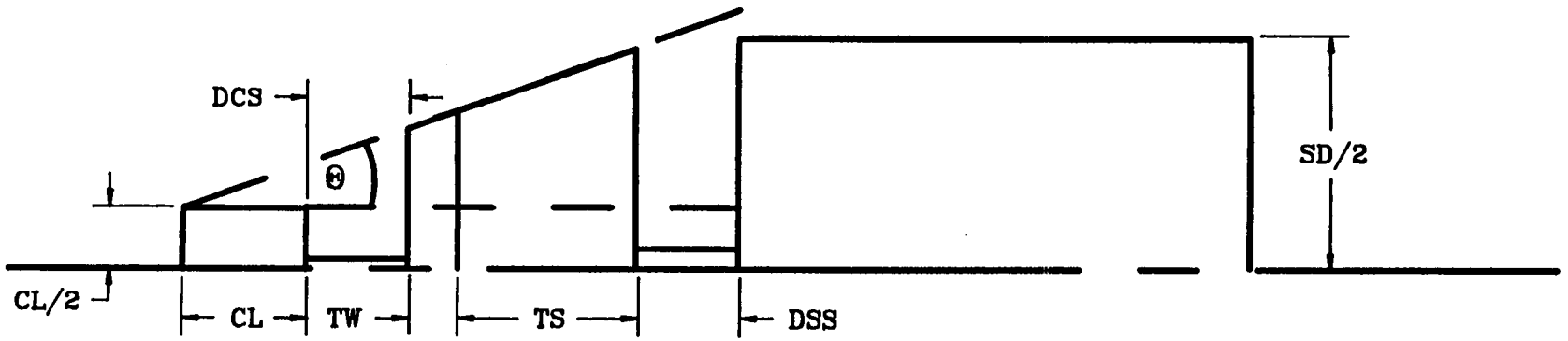


FIGURE 6-2 Neutron Absorption Cross Sections for Li-6 and Li-7 as a Function of Neutron Energy[3]



CL = core length
SD = secondary system diameter
TS = LiH shielding thickness
TW = tungsten shielding thickness
DCS = distance from core to shielding
DSS = distance from shielding to secondary

FIGURE 6-3 Parameters Needed for Solving Shielding Dimensioning

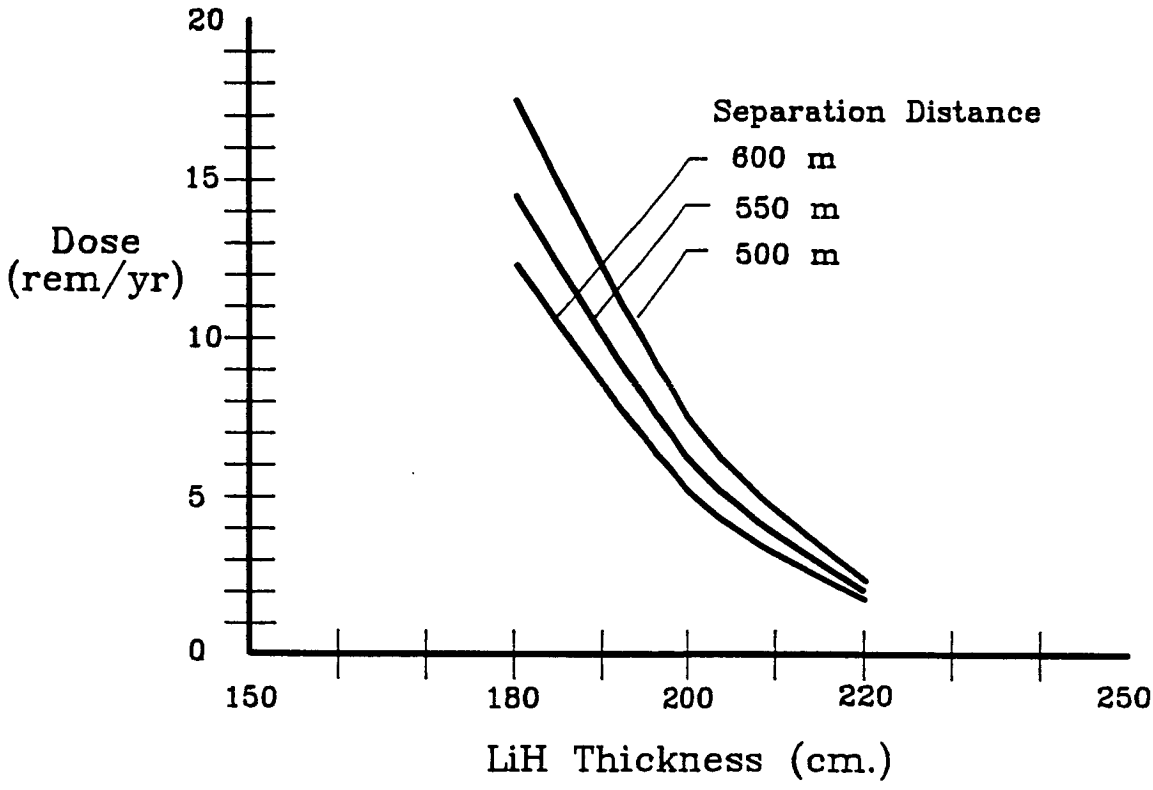


FIGURE 6–4 Total dose at the payload as a function of shielding thickness and separation distance

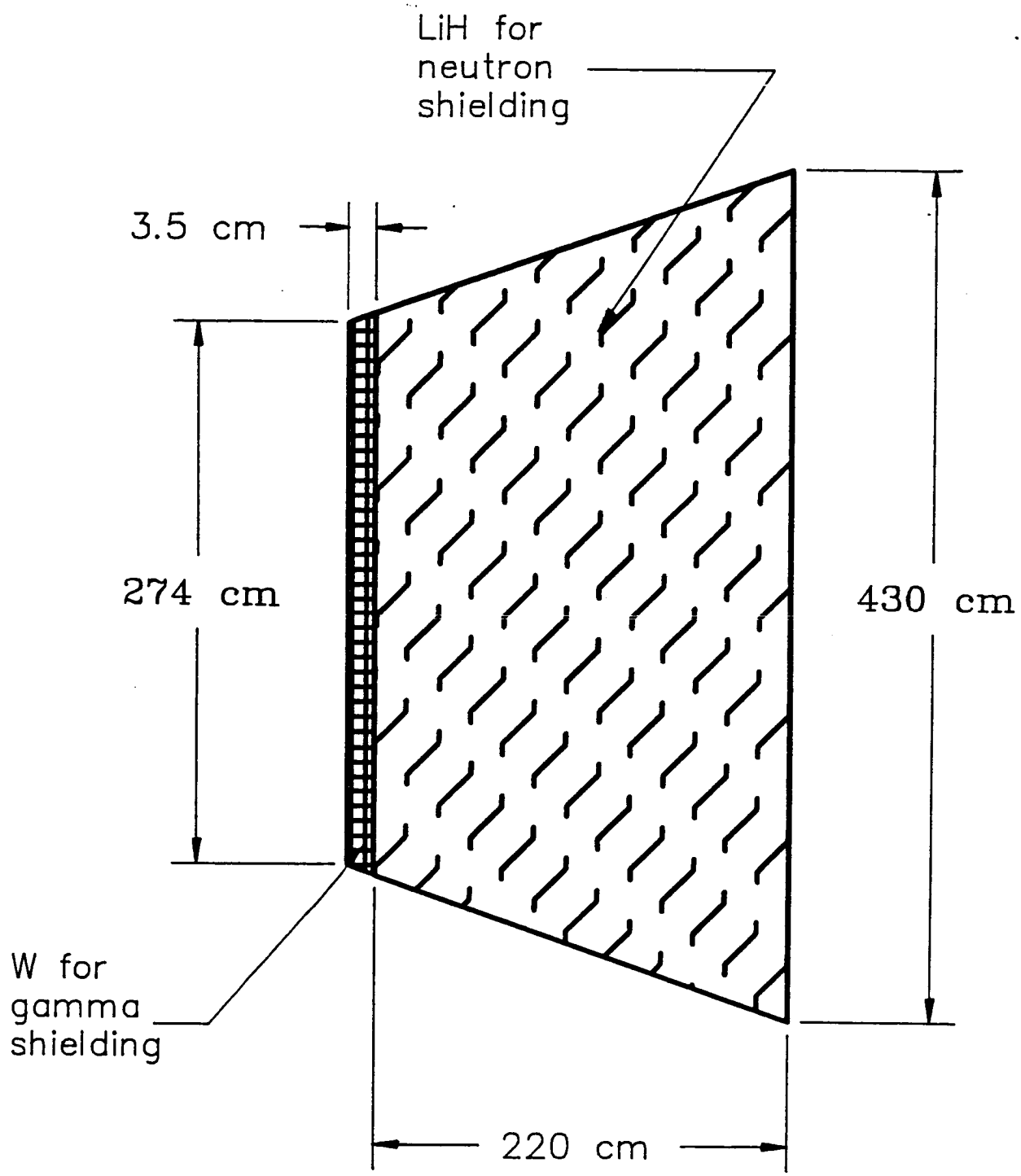


FIGURE 6-5 Shielding Dimensions

CHAPTER SEVEN: DESIGN SUMMARY

The purpose of this design was to develop a framework for future manned exploration of the outer planets. In order to meet these objectives, a high efficiency, multi-megawatt power system was required to provide the necessary power for habitation and propulsion. The high power and long mission lifetime requirement necessitated the use of a nuclear power/propulsion system. To establish the specific power and mission lifetime requirements, a manned return mission to Jupiter was selected as a reference mission. In order to complete the mission within ten years, approximately six megawatts of electrical power would be required for propulsion and life support systems. While the propellant mass has been limited to that for a return mission to Jupiter, all other systems and components have been designed for a twenty year life to allow exploration of those planets beyond Jupiter. Only the propellant mass and number of thrusters need be increased to allow such exploration. Additionally, the propellant and propulsion system are the overriding masses of the system. Since the power conversion system and payload masses represent a small fraction of the spacecraft mass, this allows flexibility in selection of payload equipment.

SYSTEM MASS

The mass estimates for the NEPTUNE system are shown in Table 7-1. The basis for the major portion of the values were calculated from actual design parameters. Other component masses, however, were taken from estimates made for the SP-100 and scaled accordingly. A brief description of the determination of each component mass is provided below.

The mass of UN fuel required for the NEPTUNE system is 4000kg/core. This was specified as an input parameter in the code CORE, used to calculate the neutronics as described in Chapter Three. The mass of the Mo-TZC cladding was calculated by determining the total volume of cladding in the core, and multiplying this by the density of the alloy. All materials masses were determined in this way. The result is a value of 1810kg/core. The mass represented by the pressure tubes and reactor vessel is approximately 62kg/core and 185kg, respectively. The mass of the reflector interior to the reactor vessel is 1630kg. The control blades represent a mass of 800kg/core, including the drive motors and the absorber located between the two cores. A minor mass consideration is the mass of the wire wrap on each of the fuel pins, at 9.5kg/core. The mass of the primary loop piping was estimated to be in the range of 3000kg.

The mass of the primary coolant is approximately 1200kg. The mass of the secondary coolant is approximately 6400kg. The mass of the turbines was based on a standard

approximation of 0.75kg/kWe for Ljungstrom turbines, giving a mass of 4500kg for each unit. The mass of the condenser, based on its dimensions and volume as done earlier for the core masses. Using this method, the condenser mass is approximately 5000kg. The pump masses were approximated as 25kg each. The mass of the radiator is 6000kg as described in Chapter Four. The shielding mass is 13700kg as described in Chapter Six. These values yield a total mass of the power conversion system of approximately 60,000kg. Using the net power generated (6.036MWe), the specific mass of the system is 9.96kg/kWe.

The mass of the propulsion system is 245,780kg, and the propellant mass is 221,000kg as described in Chapter Five. The payload mass is nominally set at 50,000kg as described in Chapter Two, but as stated earlier can be adjusted to specific mission requirements since this mass only represents a small fraction of the total spacecraft mass. For a 500m long boom as described in Chapter Six, the mass of the boom is approximately 6000kg based on using the same Ti-6%-Al-4% V alloy as used for the radiator. As an alternative, tethers could be examined for connecting the habitation portion of the spacecraft with the power conversion and propulsion systems. Using the values given, the total spacecraft mass is roughly 587,000kg.

MISSION TIME

In order to obtain estimates of trip times for a return mission to Jupiter, two different calculational methods were investigated. First, the program LOTHRUST was used. This program called for orbital dimensions, initial velocities, trip time, and specific mass of the ship to be input. The program returned specific impulse at the beginning and end of the trip. LOTHRUST computes these based on a constant acceleration assumption. This is not a valid assumption for the NEPTUNE mission; the NEPTUNE mission is one of constant thrust. Since a significant portion of the spacecraft mass is expelled as propellant during flight, this translates into a non-uniform acceleration over the life of the mission. Consequently, results from LOTHRUST analysis of the NEPTUNE trajectory were incorrect and nonapplicable.

As a second attempt at obtaining NEPTUNE orbital transfer information, a simple calculation based on an Hohmann transfer was made. The Hohmann transfer is one of minimum energy, and it is based on an initial impulse with constant tangential velocity flight during the majority of the trip. While this type of calculation is once again not entirely applicable to the NEPTUNE voyage, it was used despite its limitations to give a rough prediction for the time required to complete the orbital transfer. Using the Hohmann transfer results, it is believed that the reference mission to and from Jupiter can be completed within seven years of thrusting time. While this figure is in no way definitive, it is meant to offer a reasonable idea as to the transfer times that can be expected

with the NEPTUNE system. This seven year mission life it the figure that was used in the propellant and propulsion system calculations. A different NEPTUNE mission can be realized by simply scaling up the propellant mass and number of thrusters. The power system presented here need not be altered, and can easily accommodate mission times of up to twenty years in duration.

SYSTEM RELIABILITY

With a system lifetime goal of twenty years, reliability is a primary concern. While turbines and pumps in commercial PWR and BWR plants never run continuously for periods of time in excess of a few years, the turbines and pumps in the NEPTUNE system will be required to operated continuously for times up to twenty years. While this may seem unlikely even with machinery and materials advances that are anticipated in the upcoming years, a few features of the NEPTUNE design that may make reliability seem somewhat more plausible should be noted.

Two pumps are operated in parallel in both the primary and secondary loops. This lessens the work load of each individual pump, while at the same time offers the potential of sustained system flow at half of the designed mass flow rate in the event of a single pump failure on either the primary or secondary side. Additionally, the pressure differential supplied by the pumps is on the order of 4 atm. This is a differential pressure well below those pressures associated with larger plants, and will decrease the load and wear on pump components. Two turbines are incorporated into the NEPTUNE design for similar reasons. In the case of the turbines, however, full power could be maintained in the event of failure of a single turbine since both turbines have been rated to supply the full 6.1MWe. Each turbine is operated at pressure differentials that are relatively small, with absolute pressures that are likewise small. Thus, by operating pumps in parallel and dual turbines that supply the required power together, the reliability of the NEPTUNE system is enhanced.

Two nuclear cores, one operational and one standby, were included in the NEPTUNE design for materials reliability. Each core will need to be operated for only a period of ten years. Current experience from experimental reactors indicates that this goal is reasonable. However, in the event of the failure during operation of one of the cores, it may be possible to transfer operation to the standby core. In general, system pressures are relatively low, which is typical of liquid metal systems. This in itself greatly increases system reliability by lowering the probability of failure of all system components from pumps and turbines to fuel pins, elbows, and pipes. With all of these considerations, a twenty year system lifetime is realistic.

REFERENCES

1. Handbook of Chemistry and Physics, 68th edition, CRC Press, Boca Raton, FL, 1987.

2. Keaton, P.W., "Low-Thrust Rocket Trajectories," LA-10625-MS, Los Alamos, NM, 1986.

3. Manvi, R., Fujita, T., "SP-100 Program: Users Handbook of Basic Configurational Tradeoffs," JPLD-4154, Pasadena, CA, 1987.

4. Sutton, G.P., Ross, D.M., An Introduction to Rocket Propulsion, John Wiley & Sons, Los Angeles, CA, 1975.

Table 7-1. System Mass Summary.

POWER CONVERSION SYSTEM	
UN Fuel	4000 kg/core
Cladding	1810 kg/core
Reactor Structure	309 kg
Reflector	1630 kg
Control Blades and Drives	800 kg/core
Primary Loop Piping	3000 kg
Primary Coolant	1200 kg
Secondary Coolant	6400 kg
Turbines (total)	9000 kg
Condenser	5000 kg
Pumps (total)	200 kg
Radiator	6000 kg
Shielding	13700 kg
Total	60000 kg
PROPULSION	
Thrusters (total)	245780 kg
Propellant	221000 kg
Total	466780 kg
PAYLOAD	
Modules	50000 kg
Boom	6000 kg
Total	56000 kg

APPENDIX ONE

CODE LISTINGS

CORE

CORE NEUTRONICS CODE

```
C       THIS PROGRAM IS A MULTIGROUP DIFFUSION CODE DEVELOPED FOR
C       USE IN DESIGNING FAST REACTOR CORES. THE CODE IS WRITTEN IN
C       FORTRAN V AND OPERATES ON THE VAX COMPUTER SYSTEM. ALL
C       PROGRAM INPUT IS PLACED IN A FILE IN1.DAT, AND THE PROGRAM
C       OUTPUT INFORMATION IS PLACED IN A FILE OUT.DAT.
C
C       THE PROGRAM IS CURRENTLY SET UP TO MODEL A RIGHT CIRCULAR
C       CYLINDER CORE SHAPE. THE CORE UTILIZES UO2 FUEL AND NAK
C       LIQUID METAL COOLANT, WITH STAINLESS STEEL CLADDING.
C
C       HOWEVER, THE CODE MAY BE EASILY MODIFIED FOR USE WITH
C       OTHER GEOMETRIES, FUEL TYPES, AND COOLANTS. THE CODE IS
C       COMMENTED SO THAT USERS UNFAMILIAR WITH THE CODE MAY
C       MAKE ANY NECESSARY CHANGES WITH A MINIMUM OF EFFORT.
C
C
C       THE VARIOUS ARRAYS NECESSARY TO HOLD THE MULTIGROUP CROSS-
C       SECTION INFORMATION ARE NOW DIMENSIONED. UP TO 50 GROUPS
C       MAY BE USED, BUT THESE ARRAYS MAY BE ENLARGED IF MORE
C       ENERGY GROUPS ARE DESIRED.
C
      DIMENSION A(50,50),SGSC25(50,50),SGSC28(50,50),SGSCNA(50,50),
     *  SIGA25(50),SIGA28(50),SIGANA(50),SIGF25(50),SIGF28(50),
     *  SGTR25(50),SGTR28(50),SGTRNA(50),SSGS25(50),SSGS28(50)
      DIMENSION SSGSNA(50),SGTS25(50),SGTS28(50),SGTSNA(50),GNU25(50),
     *  GNU28(50),CHI(50),EA(50),EF(50),ETR(50),DIFF(50),GNUEF(50),
     *  EA25(50),EA28(50),EANA(50),EF25(50),EF28(50),ESC(50,50),
     *  SCXSEC(50),FLUX(50),SESC(50)
      DIMENSION SIGAO(50),SGTRO(50),EAO(50),SGSCO(50,50)
      DIMENSION SIGAK(50),SGTRK(50),EAK(50),SGSCK(50,50)
      DIMENSION SIGAFE(50),SGTRFE(50),EAFE(50),SGSCFE(50,50)
C
C       THE INPUT AND OUTPUT FILES ARE NOW INITIALED.
C
      OPEN(UNIT=5,FILE='IN1.DAT',STATUS='OLD')
      OPEN(UNIT=6,FILE='OUT.DAT',STATUS='NEW')
C
C       THE INPUT VARIABLES ARE NOW READ BY THE PROGRAM. THESE
C       VALUES ARE THE # OF NEUTRON GROUPS, FUEL ENRICHMENT,
C       THE FUEL, COOLANT, AND CLAD VOLUME FRACTIONS, TEMPERATURE,
C       ATOMIC WEIGHT OF THE COOLANT, MASS OF FUEL, REACTOR POWER,
C       AND THE FUEL PIN RADIUS.
C
      READ(5,1) N
 1    FORMAT(1I2)
      READ(5,*) ENRICH,VLRTOF,VLRTOC,VLRTOCL,TK, AWC
     * ,SYSMASS,POWER,FPR
C
C       THE MULTIGROUP, MICROSCOPIC CROSS SECTIONS ARE NOW READ
C       BY THE CODE. THE VARIABLES ARE DEFINED IN THE PROGRAM
C       USER MANUAL. NOTE THAT THE VARIABLES ARE READ IN SEQUEN-
C       TIALLY, LINE BY LINE. ALTHOUGH THIS RESULTS IN A VERY LONG
C       DATA FILE, IT IS RELATIVELY SIMPLE TO ADD OR DELETE
C       MATERIALS FROM THE CROSS SECTION SET.
C
      DO 4 I=1,N
      READ(5,*) SIGA25(I),SIGA28(I),SIGANA(I),SIGF25(I),SIGF28(I),
     *  SGTR25(I),SGTR28(I),SGTRNA(I),SIGAO(I),SGTRO(I),GNU25(I),
     *  GNU28(I),CHI(I)
      SIGA25(I)=SIGF25(I)+SIGA25(I)
      SIGA28(I)=SIGF28(I)+SIGA28(I)
 4    CONTINUE
      DO 3 I=1,N
       READ(5,*) SIGAK(I),SGTRK(I)
 3    CONTINUE
C
C       THE VALUES FOR THE GROUP TO GROUP SCATTERING CROSS SECTIONS
C       ARE NOW READ IN FROM THE DATA FILE. THE 'DO LOOPS' ARE
C       USED TO AVOID ENTERING THE ENTIRE 80*80 MATRIX OF CROSS
C       SECTION VALUES, SINCE MOST ARE EQUAL TO 0.0
C
      DO 99 I=1,2
      DO 100 K=2,6
       READ(5,*) SGSC25(I,K),SGSC28(I,K),SGSCNA(I,K),SGSCK(I,K)
     * ,SGSCO(I,K)
 100   CONTINUE
 99   CONTINUE
      DO 101 K=3,6
       I=3
       READ(5,*) SGSC25(I,K),SGSC28(I,K),SGSCNA(I,K),SGSCK(I,K)
```

```
     *  ,SGSCO(I,K)
  101   CONTINUE
        DO 102 K=4,7
         I=4
         READ(5,*) SGSC25(I,K),SGSC28(I,K),SGSCNA(I,K),SGSCK(I,K)
     *  ,SGSCO(I,K)
  102   CONTINUE
        DO 103 K=5,7
         I=5
         READ(5,*) SGSC25(I,K),SGSC28(I,K),SGSCNA(I,K),SGSCK(I,K)
     *  ,SGSCO(I,K)
  103   CONTINUE
        DO 109 M=6,16
         I=M
         L=M+1
        DO 105 K=M,L
         READ(5,*) SGSC25(I,K),SGSC28(I,K),SGSCNA(I,K),SGSCK(I,K)
     *  ,SGSCO(I,K)
  105   CONTINUE
  109   CONTINUE
        DO 110 K=2,15
         L=K+1
        DO 112 I=L,16
         SGSC25(I,K)=0.0
         SGSC28(I,K)=0.0
         SGSCNA(I,K)=0.0
         SGSCK(I,K)=0.0
         SGSCO(I,K)=0.0
  112   CONTINUE
  110   CONTINUE
        DO 113 I=1,3
        DO 114 K=7,16
         SGSC25(I,K)=0.0
         SGSC28(I,K)=0.0
         SGSCNA(I,K)=0.0
         SGSCK(I,K)=0.0
         SGSCO(I,K)=0.0
  114   CONTINUE
  113   CONTINUE
        DO 115 I=4,5
        DO 116 K=8,16
         SGSC25(I,K)=0.0
         SGSC28(I,K)=0.0
         SGSCNA(I,K)=0.0
         SGSCK(I,K)=0.0
         SGSCO(I,K)=0.0
  116   CONTINUE
  115   CONTINUE
        DO 117 I=6,14
         L=I+2
        DO 118 K=L,16
         SGSC25(I,K)=0.0
         SGSC28(I,K)=0.0
         SGSCNA(I,K)=0.0
         SGSCK(I,K)=0.0
         SGSCO(I,K)=0.0
  118   CONTINUE
  117   CONTINUE
C
C       WE WILL NOW READ THE VALUES FOR THE MO-TZC CLAD
C       FOR SIMPLICITY, MO-TZC HAS BEEN MODELED AS MOLYBDENUM.
C
        DO 119 I=1,N
        READ(5,*) SIGAFE(I),SGTRFE(I)
  119   CONTINUE
        DO 120 I=1,N
        DO 121 K=1,N
         SGSCFE(I,K)=0.0
  121   CONTINUE
  120   CONTINUE
        READ(5,*)SGSCFE(1,2),SGSCFE(2,3),SGSCFE(2,4),
     * SGSCFE(2,5),SGSCFE(3,4),SGSCFE(3,5),SGSCFE(3,6)
        DO 122 I=4,15
         K=I+1
         READ(5,*) SGSCFE(I,K)
  122   CONTINUE
C
C       WE NOW CALCULATE THE DENSITY OF THE FUEL, COOLANT,
C       AND CLADDING.
C
```

```
      RHOFL=(1.443E4)-(3.43E-1)*TK-(3.78E-5*TK**2)
      RHOFL=RHOFL*1000/(100**3)
      RHOCO=.903964-.0002335*TK
      RHOCL=10.2
C
C     CALCULATE THE ATOMIC WEIGHT OF THE FUEL
C
      AW=(235.04394*ENRICH)+(238.05082*(1.0-ENRICH))+32.0
C
C     WE NOW CALCULATE THE ATOM DENSITIES OF THE ELEMENTS
C     WITHIN THE CORE, UTILIZING THE ENRICHMENT AND VOLUME
C     FRACTIONS.
C
      AD25=((6.023E23*RHOFL)/AW)*VLRTOF*ENRICH
      AD28=((6.023E23*RHOFL)/AW)*VLRTOF*(1.0-ENRICH)
      ADO=((6.023E23*RHOFL)/AW)*VLRTOF
      ADNA=0.0
      ADK=((6.023E23*RHOCO)/AWC)*VLRTOC
      ADFE=((6.023E23*RHOCL)/95.94)*VLRTOCL
C
C     CALCULATE THE MACROSCOPIC CROSS SECTIONS
C
      DO 6 I=1,N
      EA(I)=(AD25*SIGA25(I))+(AD28*SIGA28(I))+(ADNA*SIGANA(I))
     * +(ADO*SIGAO(I))+(ADK*SIGAK(I))+(ADFE*SIGAFE(I))
      EF(I)=(AD25*SIGF25(I))+(AD28*SIGF28(I))
      ETR(I)=(AD25*SGTR25(I))+(AD28*SGTR28(I))+(ADNA*SGTRNA(I))
     * +(ADO*SGTRO(I))+(ADK*SGTRK(I))+(ADFE*SGTRFE(I))
      EA25(I)=AD25*SIGA25(I)
      EA28(I)=AD28*SIGA28(I)
      EANA(I)=ADNA*SIGANA(I)
      EAO(I)=ADO*SIGAO(I)
      EAK(I)=ADK*SIGAK(I)
      EAFE(I)=ADFE*SIGAFE(I)
      EF25(I)=AD25*SIGF25(I)
      EF28(I)=AD28*SIGF28(I)
      DIFF(I)=1.0/(3.0*ETR(I))
      GNUEF(I)=GNU25(I)*EF25(I)+GNU28(I)*EF28(I)
 6    CONTINUE
C
C     THE CALCULATED MACROSCOPIC CROSS SECTIONS ARE NOW WRITTEN
C     TO THE OUTPUT FILE. THE VALUES MAY BE CHECKED BY HAND TO
C     ENSURE THAT THE CODE IS WORKING PROPERLY.
C
C      WRITE(6,200)
C 200  FORMAT('CROSS SECTIONS AND OTHER VALUES IN THIS ORDER: EA,EF,
C     * ETR,EA25,EA28,EANA,EF25,EF28,DIFF,GNUEF,EAO,EAK,EAFE')
C      DO 45 I=1,N
C       WRITE(6,46)EA(I),EF(I),ETR(I),EA25(I),EA28(I),EANA(I),EF25(I),
C     *  EF28(I),DIFF(I),GNUEF(I),EAO(I),EAK(I),EAFE(I)
C 46   FORMAT(13F9.5)
C 45   CONTINUE
C
      DO 7 I=1,N
      DO 55 K=2,N
      ESC(I,K)=AD25*SGSC25(I,K)+AD28*SGSC28(I,K)+ADNA*SGSCNA(I,K)
     * +ADK*SGSCK(I,K)+ADO*SGSCO(I,K)+ADFE*SGSCFE(I,K)
C      WRITE(6,91)I,K,ESC(I,K)
C 91   FORMAT('ESC(I,K)=',2X,I2,2X,I2,2X,F10.5)
 55   CONTINUE
 7    CONTINUE
C
C     THE MACROSCOPIC SCATTERING CROSS SECTIONS ARE NOW
C     SUMMED FOR USE IN CALCULATING THE NEUTRON FLUX.
C
      DO 8 I=1,N
       SUM=0.
       DO 9 K=2,N
        IF(I.EQ.K) GO TO 9
        SUM=SUM+ESC(I,K)
 9     CONTINUE
       SESC(I)=SUM
C       WRITE(6,92) I,SESC(I)
C 92    FORMAT(3X,I2,2X,'SESC(I)=',F10.5)
 8    CONTINUE
C
      M=N+1
      DO 35 I=1,N
 35    ESC(M,I)=0.0
      GNUEF(M)=0.0
```

```
C
C       THE VOLUME OF THE CORE IS DETERMINED FROM THE INITIAL
C       DATA, AND THE CORE RADIUS AND BUCKLING ARE CALCULATED.
C       THESE CALCULATIONS ARE DEPENDENT ON THE CORE SHAPE,
C       AND MUST BE ALTERED IF ANOTHER GEOMETRY IS USED.
C
        VOL=((SYSMASS*1000.0)/(14.32*.935))/(VLRTOF)
        R=((VOL)/(6.28318))**.33333333
        BSQ=((2.405)/(R))**2+((3.14159)/(2.0*R))**2
C
C       THE SUBROUTINE WHICH CALCULATES THE RELATIVE GROUP
C       FLUXES AND KEFF IS NOW CALLED. THE ONLY VALUES IT RETURNS
C       ARE THE ARRAY 'FLUX' AND 'X', WHICH IS 1-KEFF.
C
        CALL BUCK (N,M,FLUX,GNUEF,X,CHI,DIFF,BSQ,EA,SESC,ESC)
 26      BSQAVG=BSQ
C
C       THE INPUT VALUES ARE NOW WRITTEN TO THE OUTPUT FILE,
C       ALONG WITH SOME OF THE NEWLY CALCULATED PARAMETERS.
C       THE LABELS ARE SELF-EXPLANATORY.
C
        RM25=SYSMASS*(AW-32.0)/(AW/ENRICH)
        RMURAN=SYSMASS*(AW-32.0)/(AW)
        RMFUEL=SYSMASS
        WRITE(6,97)RMFUEL
 97     FORMAT('TOTAL MASS OF UN FUEL IS ',F12.4,1X,'KG')
        WRITE(6,280)
        WRITE(6,98)R
 98     FORMAT('RADIUS OF THE CORE IS ',F8.3,1X,'CM')
        WRITE(6,280)
 25     WRITE(6,500) BSQAVG
 500    FORMAT('ROOT FOR THE BUCKLING',3X,'BSQ=',F10.8)
        WRITE(6,280)
        WRITE(6,161)ENRICH
 161    FORMAT('UN FUEL ENRICHMENT IS',F5.4)
        WRITE(6,280)
        WRITE(6,96)RM25
 96     FORMAT('CRITICAL MASS OF U-235 IS ',F12.4,1X,'KG')
        WRITE(6,280)
        WRITE(6,162)VLRTOF,VLRTOC,VLRTOCL
 162    FORMAT('VOLUME FRACTIONS: FUEL=',F4.3,2X,'COOLANT=',
     * F4.3,2X,'STRUCTURE=',F4.3)
        WRITE(6,280)
        WRITE(6,160)TK
 160    FORMAT('COOLANT TEMP IS',F12.3,1X,'K')
        WRITE(6,280)
        WRITE(6,209)FPR
 209    FORMAT('FUEL PIN RADIUS IS',F8.3,1X,'CM')
        WRITE(6,280)
        WRITE(6,210)X
 210    FORMAT('KEFF-1=',1X,F6.4)
        WRITE(6,280)
        WRITE(6,208)POWER
 208    FORMAT('REACTOR POWER IS',E15.5,1X,'WATTS')
        WRITE(6,280)
C
C       THIS SECTION FINDS THE TRUE GROUP FLUXES FOR THE GIVEN
C       POWER LEVEL AND CALCULATES THE CONSUMPTION RATES OF
C       U-235 AND U-238.
C
        SUM=0.0
        DO 250 I=1,N
         SUM=SUM+EF(I)*FLUX(I)
 250    CONTINUE
        AAA=(3.63)*(POWER)/((6.28318)*(R**3)*(200.0)*
     * (1.60207E-13)*(SUM))
        WRITE(6,275)AAA
 275    FORMAT('RELATIVE TO ACTUAL FLUX LEVEL CONVERSION
     * FACTOR "A" IS',E15.5)
C
C       THE RELATIVE GROUP FLUXES ARE NOW MULTIPLIED BY THE
C       REACTOR POWER CONSTANT 'AAA', AND THE ACTUAL FLUX
C       LEVELS WRITTEN TO THE OUTPUT FILE.
C
        DO 255 I=1,N
         FLUX(I)=AAA*FLUX(I)
        WRITE(6,254) I,FLUX(I)
 254    FORMAT('GROUP',I2,1X,'ACTUAL FLUX VALUE',E15.5,
     * 1X,'N/CM2-S')
 255    CONTINUE
```

```
C
C       THE CONSUMPTION RATES FOR U-235 AND U-238 ARE FOUND
C       BY MULTIPLYING THE ACTUAL FLUX LEVELS FOR EACH
C       GROUP WITH THE APPROPRIATE ABSORBTION CROSS SECTION.
C       THE RESULTS FOR EACH ENERGY GROUP ARE THEN SUMMED TO
C       FIND THE TOTAL CONSUMPTION RATE.
C
        SUM1=0.0
        SUM2=0.0
        DO 260 I=1,N
         SUM1=SUM1+EA25(I)*FLUX(I)
         SUM2=SUM2+EA28(I)*FLUX(I)
 260    CONTINUE
        CR25=(SUM1)*(6.28318)*(R**3)/(3.63)
        CR28=(SUM2)*(6.28318)*(R**3)/(3.63)
        WRITE(6,280)
        WRITE(6,261) CR25,CR28
 261    FORMAT('CONSUMPTION RATE:',1X,E15.5,1X,'AT/S',1X,'U-235',
     * 3X,E15.5,1X,'AT/S',1X,'U-238')
C
C       THE MAXIMUM VOLUMETRIC HEAT PRODUCTION IS FOUND IN
C       A SIMILAR WAY, BY FINDING THE FISSION RATE FOR EACH
C       GROUP, SUMMING THEM, AND MULTIPLYING BY THE ENERGY
C       RELEASED PER FISSION.
C
        WRITE(6,280)
        SUM=0.0
        DO 270 I=1,N
         SUM=SUM+EF(I)*FLUX(I)
 270    CONTINUE
        QVOL=(SUM)*(200.0)*(1.60207E-13)/(VLRTOF)
        WRITE(6,271) QVOL
 271    FORMAT('MAXIMUM HEAT PRODUCTION IN FUEL ELEMENT IS'
     * ,F12.4,1X,'W/CM3')
        WRITE(6,280)
C
C        CALCULATE THE MAXIMUM HEAT FLUX
C
        QVMAX=QVOL*FPR/2.0
        WRITE(6,1110)QVMAX
 1110   FORMAT('0','MAXIMUM HEAT FLUX = ',F6.2,' W/CM**2'/)
C
C       THE TOTAL NUMBER OF FUEL PINS WILL NOW BE FOUND
C       FROM THE CORE SIZE, COOLANT VOLUME FRACTION,
C       AND FUEL PIN RADIUS.
C
        FPN=(R**2)*(1.0-VLRTOC)/(FPR**2)
        WRITE(6,272) FPN
 272    FORMAT('TOTAL # OF FUEL PINS IS',F8.2)
        WRITE(6,280)
C
C       THE AVERAGE LINEAR HEAT RATE IS NOW CALCULATED
C
        QAVG=(POWER)/(2.0*R*FPN)
        WRITE(6,273) QAVG
 273    FORMAT('AVERAGE LINEAR HEAT RATE IS',F10.4,2X,'W/CM')
 280    FORMAT(/)
 999    CONTINUE
C
C       CALCULATE AVERAGE HEAT FLUX
C
        QFLUX=POWER/(3.14159*FPR*R*4.0*FPN)
        WRITE(6,1050)QFLUX
 1050   FORMAT('0','AVERAGE HEAT FLUX: ',F6.2,' W/CM**2'/)
C
C        CALCULATE CLADDING THICKNESS
C
        RF=SQRT((VLRTOF*R**2.0)/FPN)
        C=FPR-RF
        WRITE(6,1070)C
 1070   FORMAT(' ','CLADDING THICKNESS = ',F6.4,' CM'/)
C
C       CALCULATE THE MAXIMUM FUEL CENTERLINE TEMPERATURE
C
        HI=2.0*R
        KF=23.47
        KC=104.2
        H=3175.0
        PI=3.14159
        FR=FPR-C
```

```
      QS=QVOL*PI*(FR**2.0)*HI
      HI=HI/100.0
      AR=2.0*PI*FR*HI
      ARC=2.0*PI*(FPR)*HI
      AM=(AR+ARC)/(LOG(ARC/AR))
      RF=(R/100.0)/(2.0*KF*AR)
      RC=(C/100.0)/(KC*AM)
      RCO=1.0/(H*ARC)
      TCLMAX=QS*(RF+RC+RCO)+TK
C
      WRITE(6,1000)TCLMAX
 1000 FORMAT('0','MAXIMUM FUEL CENTERLINE TEMPERATURE ',F7.2,' K'/)
      PRINT*,TCLMAX
C
C     CALCULATE THE AVERAGE FUEL CENTERLINE TEMPERATURE
C
      QS=QAVG*HI*100.0
      TCLAVG=QS*(RF+RC+RCO)+(TK+800.0)/2.0
      WRITE(6,1010)TCLAVG
 1010 FORMAT(' ','AVERAGE FUEL CENTERLINE TEMPERATURE ',F7.2,' K'/)
      PRINT*,TCLAVG
C
C     CALCULATE TOTAL BURNUP IN ATOM% FOR A 10-YEAR CORE LIFE
C
      AVAIL=SYSMASS*2.3897E+24*ENRICH
      ACTUAL=CR25*3.1536E+08
      BU=(ACTUAL/AVAIL)*100.0
      WRITE(6,1020)BU
 1020 FORMAT(' ','ATOM PERCENT BURN UP: ',F6.2/)
      PRINT*,BU
C
C      CALCULATE CONVERSION RATIO
C
      CONV=CR28/CR25
C
      WRITE(6,1030)CONV
 1030 FORMAT(' ','CONVERSION RATIO: ',F4.2/)
C
C      CALCULATE FUEL ROD PITCH
C
      SIDE=SQRT(FPN)
      PITCH=(2.0*R)/SIDE
      WRITE(6,1040)PITCH
 1040 FORMAT(' ','FUEL ROD PITCH = ',F6.4,' CM'/)
C
      CLEAR=PITCH-2.0*FPR
      WRITE(6,1060)CLEAR
 1060 FORMAT(' ','CLEARANCE BETWEEN RODS = ',F6.4,' CM'/)
C
C      CALCULATE U-235 MASS BURNED OVER 10 YEAR CORE LIFE
C
      BURNED=(CR25*3.1536E+08*235.0/6.02E+23)/1000.0
      EOLMAS=SYSMASS*0.94*ENRICH-BURNED
      WRITE(6,1100)EOLMAS
 1100 FORMAT(' ','U-235 MASS REMAINING AT EOL = ',F7.2,' KG'/)
      CLOSE(UNIT=5)
      CLOSE(UNIT=6)
      STOP
      END
C
C     SUBPROGRAM TO GENERATE GROUP FLUXES AND CRITICAL BUCKLING
C
      SUBROUTINE BUCK (N,M,FLUX,GNUEF,X,CHI,DIFF,BSQ,EA,SESC,ESC)
      DIMENSION FLUX(50),GNUEF(50),CHI(50),DIFF(50),EA(50),SESC(50)
      DIMENSION ESC(50,50)
C
C     THE NEUTRON FLUXES ARE DETERMINED SEQUENTIALLY, AND
C     THEN USED TO FIND KEFF FOR THE SYSTEM. AN EXPLANATION
C     OF THESE CALCULATIONS IS GIVEN IN THE USER MANUAL.
C
      FLUX(1)=CHI(1)/(DIFF(1)*BSQ+EA(1)+SESC(1))
      DO 12 I=2,N
       SUM=0.0
       NM1=N-1
       DO 10 K=1,NM1
        IF(K.GE.I) GO TO 11
        SUM=SUM+ESC(K,I)*FLUX(K)
 10    CONTINUE
 11    CONTINUE
       Q=SUM
```

```
C
       FLUX(I)=(CHI(I)+Q)/((DIFF(I)*BSQ)+EA(I)+SESC(I))
 12    CONTINUE
       SUM=0.0
       DO 13 I=1,N
        SUM=SUM+GNUEF(I)*FLUX(I)
 13    CONTINUE
       X=SUM-1.0
       RETURN
       END
```

TDC1MOD2

FUEL ELEMENT TEMPERATURE DISTRIBUTION CODE

```
                        PROGRAM TDC1MOD2
C
C       .........performed by DANIEL E. BROZAK - Feb. 1987........
C                          a.k.a. *** WILDMAN ***
C
C     THIS PROGRAM WAS WRITTEN IN ONE DAY FOR THE CALCULATION OF
C      CLAD AND FUEL TEMPERATURES AT A GIVEN AXIAL LOCATION.  THIS
C      PROCEDURE STARTS WITH THE CLADDING OUTER SURFACE TEM-
C      PERATURE AND WORKS INWARD TOWARDS THE FUEL CENTERLINE.
C      THE ROSS AND STOUTE GAP CONDUCTANCE MODEL IS EMPLOYED.
C
C     LISTED BELOW ARE THE DESIGN PARAMETERS USED THROUGHOUT
C      THIS PROGRAM ALONG WITH THEIR FUNCTION DESCRIPTIONS.
C      NOTE: THE INPUT TEMPERATURES MUST BE IN KELVIN !!!!!
C
C     IDENT    > PIN IDENTIFICATION STRING
C     RFO      > FUEL OUTER RADIUS (CM)
C     RFI      > FUEL INNER RADIUS IF ANNULAR (CM)
C     RCO      > CLAD OUTER RADIUS (CM)
C     RCI      > CLAD INNER RADIUS (CM)
C     TFS      > FUEL SURFACE TEMPERATURE (K)
C     TFCL     > FUEL CENTERLINE TEMPERATURE (K)
C     TFRAD    > FUEL TEMPERATURE AT THAT PARTICULAR RADIUS (K)
C     TFAVG    > FUEL AVERAGE TEMPERATURE AT PEAK AXIAL LOCATION (K)
C     TFAVGVOL> AREA AVERAGE TEMPERATURE AT PEAK AXIAL LOCATION (K)
C     TCO      > CLAD OUTER SURFACE TEMPERATURE (K)
C     TCI      > CLAD INNER SURFACE TEMPERATURE (K)
C     TCAVG    > CLAD AVERAGE TEMPERATURE (K)
C     TLO      > LINER OUTER SURFACE TEMPERATURE (K)
C     TLI      > LINER INNER SURFACE TEMPERATURE (K)
C     CLTHCK   > CLADDING THICKNESS (CM)
C     LITHCK   > LINER THICKNESS (CM)
C     Q3TAVG   > TOTAL AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                AT THE GIVEN AXIAL LOCATION (W/CM**3)
C     Q3FAVG   > AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                OF THE FUEL (W/CM**3)
C     Q3CAVG   > FRACTION OF THE AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                FOR GAMMA HEATING WITHIN THE CLADDING (W/CM**3)
C     Q3LAVG   > FRACTION OF THE AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                FOR GAMMA HEATING WITHIN THE LINER (W/CM**3)
C     ALPHAC   > THERMAL EXPANSION COEFFICIENT FOR THE CLADDING (K**-1)
C     ALPHAF   > THERMAL EXPANSION COEFFICIENT FOR THE FUEL (K**-1)
C     GAPCOLD  > GAP WIDTH AT COLD CONDITIONS (CM)
C     GAPHOT   > GAP WIDTH AT HOT CONDITIONS (CM)
C     GAPTYPE  > TYPE OF BONDING USED IN THE FUEL-CLAD TYPE
C     CLTYPE   > TYPE OF CLADDING
C     FTD      > FUEL THEORETICAL DENSITY
C     ENRICH   > ENRICHMENT OF U-235 IN FUEL PELLET
C     GEOM     > SOLID OR ANNULAR FUEL PELLET
C     FLUX     > THERMAL OR FAST FLUX EXPERIENCED BY FUEL ROD
C     FTYPE    > FUEL COMPOSITION -MONO OR MIXED
C     LITYPE   > LINER COMPOSITION
C     CONV     > CONVERGENCE LIMIT USED IN CRITERIA TESTS
C     PERCCL   > PERCENTAGE OF HEATING IN CLADDING
C     PERCLI   > PERCENTAGE OF HEATING IN LINER
C
C
C     ..........................................................
C     ..........................................................
C     ..........................................................
C     ..........................................................
C     ..........................................................
C
C
C     LISTED BELOW IS A DESCRIPTION OF THE INPUT DECK - EACH
C      VARIABLE IS LISTED ON A SEPARATE LINE.  A BRIEF [NOTE]
C      WILL BE GIVEN TO EACH VARIABLE IF NEEDED.  BE SURE THAT
C      UNITS ARE CORRECT AS DESCRIBED IN PREVIOUS SECTION.
C
C     ROW 0  - NUMPIN [number of pins represented in data deck-
C              enter only once as first line in data deck]
C     ROW 1  - IDENT [maximum 20 character string]
C     ROW 2  - RFO (cm)
C     ROW 3  - RFI (cm) [a zero must be entered if pellet is solid]
C     ROW 4  - RCO (cm)
C     ROW 5  - TCO (K)
C     ROW 6  - CLTHCK (cm)
C     ROW 7  - LITHCK (cm) [a zero must be entered if no liner exists]
C     ROW 8  - Q3TAVG (W/cm**3)
C     ROW 9  - CLTYPE [0 > Nb, 1 > Ta, 2 > SS316, 3 > SS304, 4 > W-Re]
```

```
C       ROW 10 - GEOM [0 > solid, 1 > annular]
C       ROW 11 - GAPTYPE [0 > helium, 1 > sodium, 2 > lithium]
C       ROW 12 - GAPCOLD (cm)
C       ROW 13 - FTD (%)
C       ROW 14 - ENRICH (%)
C       ROW 15 - FLUX [0 > thermal, 1 > fast]
C       ROW 16 - FTYPE [0 > mono, 1 > mixed]
C       ROW 17 - LITYPE [0 > tungsten]
C       ROW 18 - CONV
C       ROW 19 - PERCCL [number is not in % format]
C       ROW 20 - PERCLI [number is not in % format]
C
C
C       THIS IS AN EXAMPLE OF AN INPUT DECK
C
C
C       ROW 0  - 1
C       ROW 1  - ORR UN3-B
C       ROW 2  - 0.3810
C       ROW 3  - 0.0
C       ROW 4  - 0.4620
C       ROW 5  - 1673
C       ROW 6  - 0.069
C       ROW 7  - 0.00762
C       ROW 8  - 632.13
C       ROW 9  - 1.0
C       ROW 10 - 0.0
C       ROW 11 - 0.0
C       ROW 12 - 0.0051
C       ROW 13 - 95.0
C       ROW 14 - 12.9
C       ROW 15 - 0.0
C       ROW 16 - 0.0
C       ROW 17 - 0.0
C       ROW 18 - 0.001
C       ROW 19 - 0.04
C       ROW 20 - 0.01
C
C
C       .....................................................
C       .....................................................
C       .....................................................
C       .....................................................
C       .....................................................
C
C
        IMPLICIT REAL*4 (A-Z)
        INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
        REAL Q,Q1
C
        DIMENSION TRADPT1(100),TRADPT2(100)
C
        COMMON/C/TCO,RCO,PERCLI,PERCCL,CLTHCK
        COMMON/G/TCI,TCAVG,GAPCOLD,TLI,GAPTYPE,TP,ITERG
        COMMON/F/GEOM,FLUX,ENRICH,RFI,ITERF
        COMMON/CandG/LITHCK,CLTYPE,LITYPE
        COMMON/GandF/FTD,Q3FAVG,FTYPE,Q,Q1
        COMMON/CandF/Q3TAVG
        COMMON/CandGandF/RFO,CONV
C
        CHARACTER IDENT*20
C
        OPEN (UNIT=1,FILE='TEMPI.DAT',STATUS='OLD')
        OPEN (UNIT=6,FILE='TEMPO.DAT',STATUS='UNKNOWN')
C
C       THESE PARAMETERS ARE USED FOR THE NUMBER OF NODE POINTS ACROSS
C        THE RADIUS IN WHICH THE FUEL TEMPERATURE DISTRIBUTION WILL
C        BE CALCULATED AND NDEG IS USED WITHIN THE POLYNOMIAL SOLVER
C        SPECIFYING THAT IT IS A CUBIC POLYNOMIAL.
C
        Q    = 10
        Q1   = Q + 1
        NDEG = 3
C
C       READ IN THE DESIGN PARAMETERS
C
        READ (1,*) NUMPIN
C
        DO 9999 NUM = 1,NUMPIN,1
C
```

```
      READ (1,262) IDENT
      READ (1,*) RFO
      READ (1,*) RFI
      READ (1,*) RCO
      READ (1,*) TCO
      READ (1,*) CLTHCK
      READ (1,*) LITHCK
      READ (1,*) Q3TAVG
      READ (1,*) CLTYPE
      READ (1,*) GEOM
      READ (1,*) GAPTYPE
      READ (1,*) GAPCOLD
      READ (1,*) FTD
      READ (1,*) ENRICH
      READ (1,*) FLUX
      READ (1,*) FTYPE
      READ (1,*) LITYPE
      READ (1,*) CONV
      READ (1,*) PERCCL
      READ (1,*) PERCLI
C
C
 262          FORMAT (A20)
             WRITE (6,101) IDENT
 101          FORMAT (///,5X,A20)
             WRITE (6,100) RFO
 100          FORMAT (5X,'RFO          > ',F8.5,' (CM)')
             WRITE (6,103) RFI
 103          FORMAT (5X,'RFI         > ',F8.5,' (CM)')
             WRITE (6,99) RCO
 99           FORMAT (5X,'RCO          > ',F8.5,' (CM)')
             WRITE (6,98) TCO
 98           FORMAT (5X,'TCO          > ',F8.2,' (K)')
             WRITE (6,97) CLTHCK
 97           FORMAT (5X,'CLTHCK       > ',F8.5,' (CM)')
             WRITE (6,96) LITHCK
 96           FORMAT (5X,'LITHCK       > ',F8.5,' (CM)')
             WRITE (6,95) Q3TAVG
 95           FORMAT (5X,'Q3TAVG       > ',F8.2,' (W/CM**3)')
             WRITE (6,92) CLTYPE
 92           FORMAT (5X,'CLTYPE       > ',F3.1)
             WRITE (6,91) GEOM
 91           FORMAT (5X,'GEOM         > ',F3.1)
             WRITE (6,90) GAPTYPE
 90           FORMAT (5X,'GAPTYPE      > ',F3.1)
             WRITE (6,89) GAPCOLD
 89           FORMAT (5X,'GAPCOLD      > ',F8.5)
             WRITE (6,88) FTD
 88           FORMAT (5X,'FTD         > ',F5.1)
             WRITE (6,87) ENRICH
 87           FORMAT (5X,'ENRICH       > ',F5.1)
             WRITE (6,86) FLUX
 86           FORMAT (5X,'FLUX         > ',F3.1)
             WRITE (6,85) FTYPE
 85           FORMAT (5X,'FTYPE        > ',F3.1)
             WRITE (6,876) LITYPE
 876          FORMAT (5X,'LITYPE       > ',F3.1)
             WRITE (6,102) CONV
 102          FORMAT (5X,'CONV         > ',F10.7)
             WRITE (6,94) PERCCL
 94           FORMAT (5X,'PERCCL       > ',F5.3)
             WRITE (6,93) PERCLI
 93           FORMAT (5X,'PERCLI       > ',F5.3)
C
C
C     ..................................................................
C     ..................................................................
C     ..................................................................
C     ..................................................................
C     ..................................................................
C
C
C     MAIN PROGRAM DRIVER
C
C     ----------
      CALL CLAD (TCI,TLI,TCAVG,Q3FAVG)
C     ----------
C
C     NEED TO GUESS AN AVERAGE FUEL TEMPERATURE AND SURFACE
C      TEMPERATURE CORRESPONDING TO THE PEAK AXIAL LOCATION.
```

```
C
      TFAVGVOL2 = TCI + 200.0
      TFS       = TCI + 100.0
      TP        = 298.2
      ITERG     = 0
      ITERF     = 0
C
C     NEED TO COMPUTE SOME TYPICAL VALUES FOR THE DISTRIBUTION OF
C      THE TEMPERATURE ACROSS THE FUEL RADIUS SO THAT A CRITERIA
C      TEST CAN BE EMPLOYED IN THE ROUTINES FOR COMPUTING THE SAME
C      TEMPERATURE DISTRIBUTION.
C
C
C     SET UP INITIAL FUEL TEMPERATURE PROFILE TO BE USED IN FUEL
C      ITERATIVE PROCESS.
C
      DO 967 JJ = 1,Q1,1
            TRADPT2(JJ) = TFS + 8.0*JJ
 967  CONTINUE
C
C     ----------
      CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,GAPHOT,
     +          CLOSEDGAP)
C     ----------
C
C
C     ----------
      CALL FUEL (TFS,TRADPT1,TRADPT2,TFAVGVOL2,TFAVG2,CLOSEDGAP)
C     ----------
C
 9999 CONTINUE
C
      STOP
      END
C
C
C     ..........................................................
C     ..........................................................
C     ..........................................................
C     ..........................................................
C     ..........................................................
C
C
      SUBROUTINE CLAD (TCI,TLI,TCAVG,Q3FAVG)
C
      IMPLICIT REAL*4 (A-Z)
      INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
C
      COMMON/C/TCO,RCO,PERCLI,PERCCL,CLTHCK
      COMMON/CandG/LITHCK,CLTYPE,LITYPE
      COMMON/CandF/Q3TAVG
      COMMON/CandGandF/RFO,CONV
C
C
C-------DESCRIBED BRIEFLY BELOW ARE ADDITIONAL PARAMETERS USED----------
C      ENTIRELY WITHIN THIS SUBROUTINE
C
C     TCAVG1 and TCAVG2 - USED AS PREVIOUS AND NEWLY CALCULATED
C                         AVERAGE CLADDING TEMPERATURES IN THE
C                         ITERATIVE PROCESS FOR CONVERGENCE TEST
C     TLAVG1 and TLAVG2 - USED AS PREVIOUS AND NEWLY CALCULATED
C                         AVERAGE LINER TEMPERATURES IN THE
C                         ITERATIVE PROCESS FOR CONVERGENCE TEST
C     KCLAD and KLINER - REPRESENTS THE THERMAL CONDUCTIVITY OF
C                        THE CLADDING AND LINER RESPECTIVELY
C     ESPC and ESPL - THE CONVERGENCE CRITERIA TEST
C-----------------------------------------------------------------------
C
C     THIS NEXT SECTION EMPLOYS AN ITERATIVE METHOD IN THE
C      COMPUTATION OF THE TEMPERATURE DROPS EXPERIENCED
C      ACROSS THE CLADDING AND LINER.
C
C
      RCI = RCO - CLTHCK
      RLO = RCI
      RLI = RLO - LITHCK
C
C     CALCULATE THE HEAT GENERATION IN LINER AND CLADDING
C
      IF (LITHCK.EQ.0.0) THEN
C
```

```
                PERCLI = 0.0
                Q3LAVG = 0.0
        ELSE
                Q3LAVG = PERCLI*Q3TAVG
C
        ENDIF
C
C       ASSUME AN INITIAL INNER CLADDING TEMPERATURE FOR ITERATION
C
                TCI = TCO + 40.0
C
                Q3CAVG = PERCCL*Q3TAVG
C
                Q3FAVG = (1.0 - PERCCL - PERCLI)*Q3TAVG
C
                Z = RCI/RCO
C
                TCAVG2 = (TCO + TCI)/2.0
 3              TCAVG1 = TCAVG2
C
                KCLAD = KC(CLTYPE,TCAVG1)
C
                TCI = TCO + (Q3CAVG/(2.0*KCLAD))*((RCO**2.0/2.0)*
     +                (1.0-RCI**2.0/RCO**2.0) + RCI**2.0*(ALOG(Z)*
     +                (1.0-(Q3FAVG/Q3CAVG)*(RFO**2.0/RCI**2.0))))
C
                TCAVG2 = (TCO + TCI)/2.0
                EPSC = ABS(TCAVG1 - TCAVG2)/TCAVG1
                IF (EPSC.GT.CONV) THEN
                        GO TO 3
                ELSE
                        WRITE (6,84) TCO
                        WRITE (6,83) TCI
                        WRITE (6,82) TCAVG2
                        GO TO 4
                ENDIF
C
C
 4      TCAVG = TCAVG2
C
C
C       THIS SECTION COMPUTES THE TEMPERATURE DROP ACROSS
C        THE LINER IF A LINER IS PRESENT.
C
        IF (LITHCK.EQ.0.0) THEN
C
                GO TO 6
C
        ELSE
C
                TLO = TCI
C
C       ASSUME AN INITIAL INNER LINER TEMPERATURE FOR ITERATION
C
                TLI = TCI + 4.0
C
                Z = RLI/RLO
C
                TLAVG2 = (TLO + TLI)/2.0
 5              TLAVG1 = TLAVG2
C
C       THIS NEXT FUNCTION COMPUTES THE CONDUCTIVITY OF THE LINER
C        (WATTS/CM*K) FOR TUNGSTEN USING THE AVERAGE LINER TEMP.
C
                KLINER = KL(LITYPE,TLAVG1)
C
                TLI = TLO + (Q3LAVG/(2.0*KLINER))*((RLO**2.0/2.0)*
     +                (1.0-RLI**2.0/RLO**2.0) + RLI**2.0*(ALOG(Z)*
     +                (1.0-(Q3FAVG/Q3LAVG)*(RFO**2.0/RLI**2.0))))
C
                TLAVG2 = (TLO + TLI)/2.0
                EPSL = ABS(TLAVG1 - TLAVG2)/TLAVG1
                IF (EPSL.GT.CONV) THEN
                        GO TO 5
                ELSE
                        WRITE (6,81) TLO
                        WRITE (6,80) TLI
                        WRITE (6,79) TLAVG2
                        GO TO 6
                ENDIF
```

```
      ENDIF
C
 84   FORMAT (/,5X,'CLAD OUTER TEMP.  > ',F8.2,' K')
 83   FORMAT (5X,'CLAD INNER TEMP.    > ',F8.2,' K')
 82   FORMAT (5X,'CLAD AVG. TEMP.     > ',F8.2,' K')
 81   FORMAT (/,5X,'LINER OUTER TEMP. > ',F8.2,' K')
 80   FORMAT (5X,'LINER INNER TEMP.   > ',F8.2,' K')
 79   FORMAT (5X,'LINER AVG. TEMP.    > ',F8.2,' K')
C
  6   CONTINUE
C
      RETURN
      END
C
C
C     ..................................................
C     ..................................................
C     ..................................................
C     ..................................................
C     ..................................................
C
C
      SUBROUTINE GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,GAPHOT,
     +                CLOSEDGAP)
C
      IMPLICIT REAL*4 (A-Z)
      INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
C
      DIMENSION TRADPT1(100),TRADPT2(100)
C
      COMMON/G/TCI,TCAVG,GAPCOLD,TLI,GAPTYPE,TP,ITERG
      COMMON/CandG/LITHCK,CLTYPE,LITYPE
      COMMON/GandF/FTD,Q3FAVG,FTYPE,Q,Q1
      COMMON/CandGandF/RFO,CONV
C
C
C-------DESCRIBED BRIEFLY BELOW ARE ADDITIONAL PARAMETERS USED----------
C       WITHIN THIS SUBROUTINE
C
C       TFAVG1 - AVERAGE FUEL TEMPERATURE
C       ALPHAC and ALPHAF - THERMAL EXPANSION COEFFICIENTS FOR
C                           CLADDING AND FUEL RESPECTIVELY
C       GAPHOT - CALCULATED GAP WIDTH AT "HOT" CONDITION DERIVED
C                SOLELY FORM THERMAL EXPANSION OF CLAD AND FUEL
C       R1CLAD, R2FUEL and R3LINER - REFER TO RESPECTIVE SURFACE
C                                    ROUGHNESSES
C       TGAVG1 and TGAVG2 - USED AS PREVIOUS AND NEWLY CALCULATED
C                           AVERAGE CLADDING TEMPERATURES IN THE
C                           ITERATIVE PROCESS FOR CONVERGENCE TEST
C       EPS - CONVERGENCE CRITERIA TEST
C-----------------------------------------------------------------------
C
 13   DO 767 LL = 1,Q1,1
           TRADPT1(LL) = TRADPT2(LL)
 767  CONTINUE
C
      ITERF  = ITERF + 1
C
      TFAVG1 = TFAVGVOL2
C
      ALPHAC = EXPC(CLTYPE,TCAVG)
C
      ALPHAF = EXPF(FTYPE,TFAVG1)
C
C
C     NEED TO COMPUTE THE HOT GAP WIDTH CORRESPONDING TO THIS
C      AVERAGE FUEL TEMPERATURE AND THE ITERATIVE AVERAGED
C      CLAD TEMPERATURE CALCULATED IN THE PREVIOUS SECTION.
C
C
      GAPHOT = (RFO + GAPCOLD)*(1.0 + ALPHAC*(TCAVG - TP))
     +          - RFO*(1.0 + ALPHAF*(TFAVG1 - TP))
C
C     SET UP FLAG TO DETERMINE WHETHER GAP IS CLOSED OR OPEN:
C      CLOSEDGAP = 1.0 = OPEN; CLOSEDGAP = 0.0 = CLOSED
C
      CLOSEDGAP = 1.0
C
C     CALCULATE MEAN GAP THICKNESS CORRESPONDING TO SURFACE ROUGHNESS
C
```

```
            IF (LITHCK.EQ.0.0) THEN
              R1CLAD   = R1(CLTYPE)
              R2FUEL   = R2(FTYPE)
              MEAN     = (R1CLAD**2.0 + R2FUEL**2.0)/2.0
              MEANGAP = SQRT(MEAN)
            ELSE
              R2FUEL   = R2(FTYPE)
              R3LINER  = R3(LITYPE)
              MEAN     = (R2FUEL**2.0 + R3LINER**2.0)/2.0
              MEANGAP = SQRT(MEAN)
            ENDIF
C
C       SET UP NEW GAP FLAG IF GAPHOT IS LESS THAN MEANGAP.
C
            IF (GAPHOT.LE.MEANGAP) THEN
C
              GAPHOT = MEANGAP
C
              CLOSEDGAP = 0.0
C
            ENDIF
C
C
C
C       THESE SECTIONS CALCULATE THE TEMP DROP ACROSS THE HOT
C        GAP WIDTH UNDER CERTAIN FUEL GEOMETRIES AND BONDING
C        MATERIAL.  IF GAPTYPE = 0  > HELIUM, IF GAPTYPE = 1
C        > SODIUM,  ALL KGAP'S ARE IN UNITS OF WATTS/CM*K
C        NOW DETERMINE THE PRESSURE INCREASE USING THE IDEAL GAS
C        LAW RELATIONSHIP P1/T1 = P2/T2
C
C       THIS NEXT SECTION COMPUTES THE GAP CONDUCTIVITY FOR THE GAS
C        AND CONTACT POINTS(SEE NOTE) WHEN GAP CLOSURE HAS BEEN REACHED.
C        BELOW IS A SUMMARY OF THE FORMULAS USED IN THIS CALCULATION.
C        IN SELECTION OF THESE FORMULAS PRESSURE WAS TO BE INDEPENDENT
C        AS POSSIBLE BECAUSE APPROACH IS NOT A MECHANICAL ANALYSIS.
C
C        REF: FOR H(GAS)-FUNDAMENTAL ASPECTS OF NUCLEAR REACTOR FUEL
C        ELEMENTS BY D.R. OLANDER, P. 136.
C
C        REF: FOR H(SOLID)-REVIEW OF METHODS APPLICABLE TO THE CAL-
C        CULATION OF GAP CONDUCTANCE IN ZIRCALOY-CLAD UO2 FUEL RODS
C        BY D.D. LANNING AND C.R. HANN, BNWL-1894 UC-78B, P. 14.
C        ----------------------NOTE-----------------------------
C        THIS PROGRAM DOES NOT COMPUTE H(SOLID) IF CONTACT BETWEEN
C        CLADDING AND FUEL OCCURS BECAUSE OF ITS INABILITY TO COMPUTE
C        THE INTERFACIAL PRESSURE.  HOWEVER THIS FORMULA WAS STILL
C        PROGRAMMED WITH COMMENTS(NOTED BY "CC") WITHIN THE CODE IN
C        THE EVENT THAT THE CONTACT PRESSURE COULD BE DETERMINED.
C
C        THE ACCOMMODATION COEFFICIENTS WERE REFERENCED FROM THERMAL
C        ANALYSIS OF PRESSURIZED WATER REACTORS BY L.S. TONG AND
C        J. WEISMAN, P. 99.  ALSO THIS REFERENCE PROVIDES A GRAPH
C        FOR A QUICK CHECK ON THE TOTAL HEAT TRANSFER COEFF. FOR A
C        PARTICULAR GAP WIDTH, P. 98. FUNDAMENTAL ASPECTS OF NUCLEAR
C        REACTOR FUEL ELEMENTS, D.R. OLANDER, P. 138. ALSO GAP
C        CONDUCTANCE IN ZIRCALOY-CLAD LWR FUEL RODS, J.B. AINSCOUGH,
C        P. 9 & 20, ND-R-699(S)
C
C       H = H(GAS) + H(SOLID)
C
C       H(GAS) = K(GAS)/(D + G1 +G2) WHERE
C         K(GAS) > CONDUCTIVITY OF THE GAS MIXTURE (W/CM-C)
C         D      > ACTUAL FUEL-CLAD GAP DIMENSION (CM)
C         G1-G2  > TEMPERATURE JUMP DISTANCES OF FUEL & CLAD (CM)
C
C         THE JUMP DISTANCES ARE COMPUTED USING THIS CORRELATION
C          FROM THE GAPCON EQUATION
C
C         G1 = G2 = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
C     +               LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
C         ACC      > THERMAL ACCOMMODATION COEFF. FOR THE GAS & SURFACE
C         GAMMA    > Cp/Cv = 5/3 FOR MONOATOMIC GASES (NO UNITS)
C         LAMDAHe  > MEAN FREE PATH AT 1 ATM. AND DEGREE CELCIUS (ATM-CM)
C         TGAVG1   > AVERAGE TEMPERATURE IN DEGREE KELVIN (K)
C         PR       > PRANDTL NUMBER 0.70 (NO UNITS)
C         P2       > PRESSURE IN ATMOSPHERES
C
CC      H(SOLID) = 1.189*2*K1*K2*PA/(H*(K1 + K2)*(R1**2 + R2**2)**.25)
```

```
CC
CC        K1    > THERMAL COND. OF CLAD AT INNER SURFACE TEMP. (W/CM-C)
CC        K2    > THERMAL COND. OF FUEL AT SURFACE TEMP. (W/CM-C)
CC        PA    > THE APPARENT INTERFACIAL PRESSURE (PSI)
CC        H     > THE MEYER HARDNESS OF THE SOFTER MATERIAL (PSI)
CC        R1    > MEAN ROUGHNESS OF THE CLAD (CM)
CC        R2    > MEAN ROUGHNESS OF THE FUEL (CM)
C
C       ****************************************************************
C
        IF ((GAPTYPE.EQ.0.0).AND.(LITHCK.EQ.0.0)) THEN
C
                P1 = 14.7
                T1 = 298.2
C
 8              TGAVG1 = (TFS + TCI)/2.0
C
                ITERG = ITERG + 1
C
C         THE HELIUM CONDUCTIVITY WAS REFERENCED FROM CRC HANDBOOK
C          OF CHEMISTRY AND PHYSICS 66TH EDITION, P. E-3.
C
                IF (TGAVG1.LE.1000.0) THEN
                      KGAPHE = 0.000003032*TGAVG1 + 0.000631
                ELSE
                      KGAPHE = 0.000002507*TGAVG1 + 0.001167
                ENDIF
C
C
                P2 = P1*(TGAVG1)/(T1)
C
                   ACC = 0.425 - 2.3E-4*TGAVG1
                     IF (ACC.LT.0.08) THEN
                           ACC = 0.08
                     ENDIF
C
                   GAMMA   = 5.0/3.0
                   PR      = 0.70
                   LAMDAHe = 1.74E-5
C
CC       FOR THE CASE OF H(SOLID):
CC
CC                 PA      = P2
CC                 HMEYERC = MEYERC(CLTYPE)
CC
CC                 KTCI    = KC(CLTYPE,TCI)
CC
CC                 KTFS    = KFGAP(FTYPE,TFS,FTD)
CC
CC                 R1CLAD  = R1(CLTYPE)
CC                 R2FUEL  = R2(FTYPE)
C
C
C
                IF (CLOSEDGAP.EQ.0.0) THEN
C
                   G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                 LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
                   HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
CC       IF CLOSEDGAP = 0.0 THEN CONTACT HAS TAKEN PLACE AND THE
CC       H(SOLID) WOULD HAVE BEEN COMPUTED BELOW.  HOWEVER THIS
CC       CANNOT BE DETERMINED BECAUSE OF THE INABILITY TO COMPUTE
CC       THE INTERFACIAL PRESSURE.  THEREFORE ONLY H(GAS) WILL BE
CC       EMPLOYED.
CC
CC                 HSOL = 1.189*2.0*KTCI*KTFS*PA/
CC    +                   (HMEYERC*(R1CLAD**2.0 + R2FUEL**2.0)**0.25*
CC     +                   (KTCI + KTFS))
CC
CC                 HGAP = HGAS + HSOL
C
                   HGAP = HGAS
C
                ELSE
C
                   G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                 LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
```

```
                  HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
                  HGAP = HGAS
C
               ENDIF
C
C
               Q2FAVG = Q3FAVG*RFO/2.0
C
               TFS = Q2FAVG/HGAP + TCI
C
               TGAVG2 = (TFS + TCI)/2.0
C
               EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
               IF (EPS.GT.CONV) THEN
                       P1 = P2
                       T1 = TGAVG1
C
                       GO TO 8
               ELSE
                       GO TO 12
               ENDIF
C
        ENDIF
C
C       ****************************************************************
C
        IF ((GAPTYPE.EQ.O.O).AND.(LITHCK.GT.O.O)) THEN
C
               P1 = 14.7
               T1 = 298.2
C
 9             TGAVG1 = (TFS + TLI)/2.0
C
               ITERG = ITERG + 1
C
C
C         THE HELIUM CONDUCTIVITY WAS REFERENCED FROM CRC HANDBOOK
C          OF CHEMISTRY AND PHYSICS 66TH EDITION, P. E-3.
C
               IF (TGAVG1.LE.727.0) THEN
                       KGAPHE = 0.000003032*TGAVG1 + 0.000631
               ELSE
                       KGAPHE = 0.000002507*TGAVG1 + 0.001167
               ENDIF
C
               P2 = P1*(TGAVG1)/(T1)
C
                  ACC = 0.425 - 2.3E-4*TGAVG1
                    IF (ACC.LT.O.08) THEN
                          ACC = 0.08
                    ENDIF
C
                  GAMMA    = 5.0/3.0
                  PR       = 0.70
                  LAMDAHe  = 1.74E-5
C
CC       FOR THE GAS OF H(SOLID)
CC
CC                PA       = P2
CC                HMEYERL  = MEYERL(LITYPE)
CC
CC                KTLI     = KL(LITYPE,TLI)
CC
CC                KTFS     = KFGAP(FTYPE,TFS,FTD)
CC
CC                R2FUEL   = R2(FTYPE)
CC                R3LINER  = R3(LITYPE)
C
C
C
               IF (CLOSEDGAP.EQ.O.O) THEN
C
                  G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
                  HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
CC       IF CLOSEDGAP = O.O THEN CONTACT HAS TAKEN PLACE AND THE
```

```
CC       H(SOLID) WOULD HAVE BEEN COMPUTED BELOW.  HOWEVER THIS
CC       CANNOT BE DETERMINED BECAUSE OF THE INABILITY TO COMPUTE
CC       THE INTERFACIAL PRESSURE.  THEREFORE ONLY H(GAS) WILL BE
CC       EMPLOYED.
CC
CC                HSOL = 1.189*2.0*KTLI*KTFS*PA/
CC     +                 (HMEYERL*(R2FUEL**2.0 + R3LINER**2.0)**0.25*
CC     +                 (KTLI + KTFS))
CC
CC                HGAP = HGAS + HSOL
C
                  HGAP = HGAS
C
               ELSE
C
                  G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
                  HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
                  HGAP = HGAS
C
               ENDIF
C
C              ____________________________________
               Q2FAVG = Q3FAVG*RFO/2.0
C
               TFS = Q2FAVG/HGAP + TLI
C
               TGAVG2 = (TFS + TLI)/2.0
C
               EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
               IF (EPS.GT.CONV) THEN
                       P1 = P2
                       T1 = TGAVG1
C
                       GO TO 9
               ELSE
                       GO TO 12
               ENDIF
C
         ENDIF
C
C        ********************************************************************
         IF (GAPTYPE.EQ.1.0) THEN
C
  10             TGAVG1 = (TFS + TCI)/2.0
C
                 ITERG = ITERG + 1
C
C        THE SODIUM CONDUCTIVITY WAS REFERENCED FROM BASIC HEAT TRANSFER
C         BY M. NECATI OZISIK, P. 499.
C
                 KGAPNA = -0.0004333*TGAVG1 + 1.005
C
                 ZP = RFO*(1.0 + ALPHAF*(TFAVG1 - TP))
                 Z  = (ZP + GAPHOT)/ZP
C
            IF (LITHCK.EQ.0.0) THEN
                 TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPNA) + TCI
C
                 TGAVG2 = (TFS + TCI)/2.0
            ELSE
                 TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPNA) + TLI
C
                 TGAVG2 = (TFS + TLI)/2.0
            ENDIF
C
                 EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
                 IF (EPS.GT.CONV) THEN
                         GO TO 10
                 ELSE
                         GO TO 12
                 ENDIF
C
         ENDIF
C
C
```

```
C       ************************************************************
        IF (GAPTYPE.EQ.2.0) THEN
C
 15             TGAVG1 = (TFS + TCI)/2.0
C
                ITERG = ITERG + 1
C
C       THE LITHIUM CONDUCTIVITY WAS REFERENCED FROM BASIC HEAT TRANSFER
C        BY M. NECATI OZISIK, P. 504.
C
                KGAPLI = -0.02412*TGAVG1 + 55.1
C
                ZP = RFO*(1.0 + ALPHAF*(TFAVG1 - TP))
                Z  = (ZP + GAPHOT)/ZP
C
             IF (LITHCK.EQ.0.0) THEN
                TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPLI) + TCI
C
                TGAVG2 = (TFS + TCI)/2.0
             ELSE
                TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPLI) + TLI
C
                TGAVG2 = (TFS + TLI)/2.0
             ENDIF
C
                EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
                IF (EPS.GT.CONV) THEN
                        GO TO 15
                ELSE
                        GO TO 12
                ENDIF
C
        ENDIF
C
 12     CONTINUE
C
        RETURN
        END
C
C       ..............................................................
C       ..............................................................
C       ..............................................................
C       ..............................................................
C       ..............................................................
C
C
        SUBROUTINE FUEL (TFS,TRADPT1,TRADPT2,TFAVGVOL2,TFAVG2,CLOSEGAP)
C
        IMPLICIT REAL*4 (A-Z)
        INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
C
        DIMENSION TRADPT1(100),TRADPT2(100)
C
        COMMON/F/GEOM,FLUX,ENRICH,RFI,ITERF
        COMMON/CandF/Q3TAVG
        COMMON/GandF/FTD,Q3FAVG,FTYPE,Q,Q1
        COMMON/CandGandF/RFO,CONV
C
C
C-------DESCRIBED BRIEFLY BELOW ARE ADDITIONAL PARAMETERS USED----------
C        WITHIN THIS SUBROUTINE
C
C       K - INVERSE DIFFUSION LENGTH OF CORRESPONDING FUEL
C       PP and C - USED AS PART OF INTEGRAL THERMAL CONDUCTIVITY
C                  FORMULATION
C       PART and TRAD - USED TO FIND FUEL TEMPERATURE AT PARTICULAR
C                       RADIUS POSITION DETERMINED FORM PARAMETER [I]
C-----------------------------------------------------------------------
C
C
C       THIS SECTION COMPUTES THE TEMPERATURE DISTRIBUTION ACROSS
C        THE FUEL PELLET FOR VARIOUS PELLET GEOMETRIES AND FLUXES.
C        THERE ARE TWO TYPES AND GEOMETRIES (SOLID & ANNULAR) AND
C        TWO TYPES OF FLUXES (THERMAL & FAST).  THE PARTICULAR
C        COMBINATION OF INTEREST WILL BE DETERMINED BY THE INPUT
C        DATA. NOTATION: IF GEOM = 0 > SOLID, IF GEOM = 1 > ANNULAR,
C        IF FLUX = 0 > THERMAL, IF FLUX = 1 > FAST, IF FTYPE = 0 >
C        UN (MONONITRIDE), IF FTYPE = 1 > UPuN (MIXNITRIDE)
C        ALL THE DERIVATIONS FOR THE FUEL DISTRIBUTION FORMULAS
```

```
C        WERE DERIVED AND REFERENCED IN THE ATTACHED APPENDICES.
C
C
C
C       ....................SOLID/THERMAL/MONO OR MIX.................
C
 1000   IF ((GEOM.EQ.0.0).AND.(FLUX.EQ.0.0)) THEN
C
           IF (FTYPE.EQ.0.0) THEN
                K = KUN(ENRICH,FTD)
           ELSE
                K = KUPUN(ENRICH,FTD)
           ENDIF
C
                V = K*RFO
                BI00 = BSI0(V)
                BI10 = BSI1(V)
C
                Q3KNOT = K*RFO*Q3FAVG/(2.0*BI10)
                PP = 1.0 - FTD/100.0
C
                SUMVOL = 0.0
                SUM    = 0.0
                PT     = 0
                I      = RFO/Q
C
                DO 21 RAD = 0.0,RFO,I
                   PT = PT + 1
                   V = K*RAD
                   BIOR = BSIO(V)
C
           IF (FTYPE.EQ.0.0) THEN
C
                C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                   PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                    100.0*((Q3KNOT/K**2)*
     +                    (BI00 - BIOR))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            0.91111*(T**0.45504) [BEFORE INTEGRATION]
C            (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
           ELSE
C
                C = (1.0 - PP)/(1.0 + PP)
C
                   PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                    100.0*((Q3KNOT/K**2)*
     +                    (BI00 - BIOR))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            1.74900*(T**0.34123) [BEFORE INTEGRATION]
C            (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
           ENDIF
C
                IF (PT.EQ.1) THEN
                  TRADVOL = TRAD*(RAD + I/2.0)**2.0
                ENDIF
                IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                  TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                            (RAD - I/2.0)**2.0)
                ENDIF
                IF (PT.EQ.Q1) THEN
                  TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
```

```
                  ENDIF
C
                  SUMVOL = SUMVOL + TRADVOL
C
                  TRADPT2(PT) = TRAD
C
                  SUM = SUM + TRAD
C
 21             CONTINUE
C
C       THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C        AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
        TFAVGVOL2 = SUMVOL/RFO**2.0
        TFAVG2 = SUM/Q1
C
        DO 2001 KK = 1,Q1,1
                EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                  IF (EPSF.GT.CONV) THEN
                     CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                         GAPHOT,CLOSEDGAP)
                     GO TO 1000
                  ENDIF
 2001   CONTINUE
C
        WRITE (6,751)
 751    FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
           DO 31 P = 1,Q1,1
             WRITE (6,41) P, TRADPT2(P)
 41          FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
 31        CONTINUE
C
        WRITE (6,511) TFAVGVOL2
 511    FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
        WRITE (6,51) TFAVG2
 51     FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
        GO TO 999
C
        ENDIF
C
C
C
C
C       ....................SOLID/FAST/MONO OR MIX....................
C
 1001   IF ((GEOM.EQ.0.0).AND.(FLUX.EQ.1.0)) THEN
C
                PP = 1.0 - FTD/100.0
C
                SUMVOL = 0.0
                SUM    = 0.0
                PT     = 0
                I      = RFO/Q
C
                DO 23 RAD = 0.0,RFO,I
                   PT = PT + 1
C
           IF (FTYPE.EQ.0.0) THEN
C
                C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                   PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                     100.0*((Q3TAVG/4)*
     +                     (RFO**2.0 - RAD**2.0))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            0.91111*(T**0.45504) [BEFORE INTEGRATION]
C            (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
```

```
            ELSE
C
                  C = (1.0 - PP)/(1.0 + PP)
C
                     PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                      100.0*((Q3TAVG/4)*
     +                      (RFO**2.0 - RAD**2.0))/C
C
C
C        THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C         FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C         THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C         DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C              1.74900*(T**0.34123) [BEFORE INTEGRATION]
C              (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                     TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
            ENDIF
C
                     IF (PT.EQ.1) THEN
                       TRADVOL = TRAD*(RAD + I/2.0)**2.0
                     ENDIF
                     IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                       TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                                 (RAD - I/2.0)**2.0)
                     ENDIF
                     IF (PT.EQ.Q1) THEN
                       TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
                     ENDIF
C
                     SUMVOL = SUMVOL + TRADVOL
C
                     TRADPT2(PT) = TRAD
C
                     SUM = SUM + TRAD
C
  23              CONTINUE
C
C        THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C         AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
         TFAVGVOL2 = SUMVOL/RFO**2.0
         TFAVG2 = SUM/Q1
C
         DO 2003 KK = 1,Q1,1
                 EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                   IF (EPSF.GT.CONV) THEN
                      CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                          GAPHOT,CLOSEDGAP)
                      GO TO 1001
                   ENDIF
  2003   CONTINUE
C
         WRITE (6,753)
  753    FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
            DO 33 P = 1,Q1,1
              WRITE (6,43) P, TRADPT2(P)
  43          FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
  33        CONTINUE
C
         WRITE (6,513) TFAVGVOL2
  513    FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
         WRITE (6,53) TFAVG2
  53     FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
         GO TO 999
C
         ENDIF
C
C
C
C        ..................ANNULAR/THERMAL/MONO OR MIX.................
C
  1002   IF ((GEOM.EQ.1.0).AND.(FLUX.EQ.0.0)) THEN
C
```

```
            IF (FTYPE.EQ.0.0) THEN
                 K = KUN(ENRICH,FTD)
            ELSE
                 K = KUPUN(ENRICH,FTD)
            ENDIF
C
                 V = K*RFI
                 BIOI = BSIO(V)
                 BI1I = BSI1(V)
                 BKOI = BSKO(V)
                 BK1I = BSK1(V)
                 V = K*RFO
                 BK10 = BSK1(V)
                 BI00 = BSIO(V)
                 BI10 = BSI1(V)
                 BKOO = BSKO(V)
C
                 Q3KNOT = (Q3FAVG*(RFO**2 - RFI**2)*K)/
     +                    (2.0*RFO*(BI10 - BI1I*BK10/BK1I))
     +
C
                 PP = 1.0 - FTD/100.0
C
                 SUMVOL = 0.0
                 SUM    = 0.0
                 PT     = 0
                 I      = (RFO - RFI)/Q
C
                 DO 25 RAD = RFI,RFO,I
                    PT = PT + 1
                    V = K*RAD
                    BIOR = BSIO(V)
                    BKOR = BSKO(V)
C
            IF (FTYPE.EQ.0.0) THEN
C
                 C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                    PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                     100.0*((Q3KNOT/K**2)*
     +                     (BI00 - BIOR + BI1I/BK1I*(BKOO - BKOR)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C             0.91111*(T**0.45504) [BEFORE INTEGRATION]
C             (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                 TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
            ELSE
C
                 C = (1.0 - PP)/(1.0 + PP)
C
                    PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                     100.0*((Q3KNOT/K**2)*
     +                     (BI00 - BIOR + BI1I/BK1I*(BKOO - BKOR)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C             1.74900*(T**0.34123) [BEFORE INTEGRATION]
C             (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                 TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
            ENDIF
C
                 IF (PT.EQ.1) THEN
                   TRADVOL = TRAD*(RAD + I/2.0)**2.0
                 ENDIF
                 IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                   TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                             (RAD - I/2.0)**2.0)
```

```
                  ENDIF
                  IF (PT.EQ.Q1) THEN
                    TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
                  ENDIF
C
                  SUMVOL = SUMVOL + TRADVOL
C
                  TRADPT2(PT) = TRAD
C
                  SUM = SUM + TRAD
C
 25             CONTINUE
C
C       THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C        AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
        TFAVGVOL2 = SUMVOL/RFO**2.0
        TFAVG2 = SUM/Q1
C
        DO 2005 KK = 1,Q1,1
                EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                  IF (EPSF.GT.CONV) THEN
                     CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                          GAPHOT,CLOSEDGAP)
                     GO TO 1002
                  ENDIF
 2005   CONTINUE
C
        WRITE (6,755)
 755    FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
           DO 35 P = 1,Q1,1
             WRITE (6,45) P, TRADPT2(P)
 45          FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
 35        CONTINUE
C
        WRITE (6,515) TFAVGVOL2
 515    FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
        WRITE (6,55) TFAVG2
 55     FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
        GO TO 999
C
        ENDIF
C
C
C
C       ....................ANNULAR/FAST/MONO.....................
C
 1003   IF ((GEOM.EQ.1.0).AND.(FLUX.EQ.1.0)) THEN
C
                  PP = 1.0 - FTD/100.0
C
                  SUMVOL = 0.0
                  SUM    = 0.0
                  PT     = 0
                  I      = (RFO - RFI)/Q
C
                  DO 27 RAD = RFI,RFO,I
                     PT = PT + 1
                     Z = RAD/RFO
C
        IF (FTYPE.EQ.0.0) THEN
C
                  C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                     PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                       100.0*((Q3TAVG/2)*
     +                       (RFI**2.0*ALOG(Z) + RFO**2.0/2.0*
     +                       (1.0 - (RAD/RFO)**2.0)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C             0.91111*(T**0.45504) [BEFORE INTEGRATION]
```

```
C             (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                   TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
          ELSE
C
               C = (1.0 - PP)/(1.0 + PP)
C
                   PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                    100.0*((Q3TAVG/2)*
     +                    (RFI**2.0*ALOG(Z) + RFO**2.0/2.0*
     +                    (1.0 - (RAD/RFO)**2.0)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C             1.74900*(T**0.34123) [BEFORE INTEGRATION]
C             (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                   TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
        ENDIF
C
                   IF (PT.EQ.1) THEN
                     TRADVOL = TRAD*(RAD + I/2.0)**2.0
                   ENDIF
                   IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                     TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                                (RAD - I/2.0)**2.0)
                   ENDIF
                   IF (PT.EQ.Q1) THEN
                     TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
                   ENDIF
C
                   SUMVOL = SUMVOL + TRADVOL
C
                   TRADPT2(PT) = TRAD
C
                   SUM = SUM + TRAD
C
 27             CONTINUE
C
C       THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C        AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
        TFAVGVOL2 = SUMVOL/RFO**2.0
        TFAVG2 = SUM/Q1
C
        DO 2007 KK = 1,Q1,1
                EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                  IF (EPSF.GT.CONV) THEN
                     CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                         GAPHOT,CLOSEDGAP)
                     GO TO 1003
                  ENDIF
 2007   CONTINUE
C
        WRITE (6,757)
 757    FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
           DO 37 P = 1,Q1,1
             WRITE (6,47) P, TRADPT2(P)
 47          FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
 37        CONTINUE
C
        WRITE (6,517) TFAVGVOL2
 517    FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
        WRITE (6,57) TFAVG2
 57     FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
        GO TO 999
C
        ENDIF
C
C
```

```
 999     CONTINUE
C
C
C       WRITE (6,*) 'ITERF      > ',ITERF
C
        WRITE (6,78) TFS
        WRITE (6,77) TGAVG2
C       WRITE (6,*)  'ITERG     > ',ITERG
C
 78     FORMAT (/,5X,'FUEL SURFACE TEMP.        > ',F8.2,' K')
 77     FORMAT (5X,'GAP AVERAGE TEMP.   > ',F8.2,' K')
C
        WRITE (6,1987) GAPHOT
 1987   FORMAT (/,5X,'"HOT" GAP WIDTH   > ',E15.8,' cm')
C
        IF (CLOSEDGAP.EQ.1.0) THEN
C
          WRITE (6,1986)
 1986     FORMAT (5X,'PCI               >  NO ')
C
        ELSE
C
          WRITE (6,1985)
 1985     FORMAT (5X,'PCI               >  YES ')
C
        ENDIF
C
C
        RETURN
        END
C
C
C       ..........................................................
C       ..........................................................
C       ..........................................................
C       ..........................................................
C       ..........................................................
C
C
        REAL FUNCTION KUN(ENRICH,FTD)
                IMPLICIT REAL (A-Z)
C
C         BELOW ARE THE CONSTANTS AND ATOMIC WEIGHTS USED IN THE
C          CALCULATION OF THE ATOMIC DENSITY WHICH WILL BE THEN USED
C          TO FIND THE INVERSE OF THE DIFFUSION LENGTH FOR A GIVEN
C          ENRICHMENT.
C
          AVO     = 6.022E23
          U235    = 235.04394
          U238    = 238.05082
          UNAT    = 238.07000
          N14     = 14.0080
C
C         THE DENSITY OF THE FUEL IS COMPUTED BY DENSITY(100%)*(%TD)
C          FUEL DENSITY IN UNITS OF G/CM**3
C
          DENSUN = (14.32)*(FTD/100.0)
C
C         BELOW ARE THE NECESSARY CROSS SECTIONS OF THE UN FUEL
C
          CAPU235  = 101.0E-24
          CAPU238  = 2.730E-24
          FISU235  = 577.0E-24
          SCATUNAT = 8.300E-24
          SCATN14  = 10.00E-24
          ABSN14   = 1.880E-24
C
C         THIS SECTION FINDS THE NUMBER DENSITY (ND) OF UN AND
C          FROM THIS THE INDIVIDUAL NUMBER DENSITIES OF THE
C          CONSTITUENTS.
C
          NDUN = (DENSUN*AVO)/(U235*ENRICH/100.0 +
     +            (1.0 - ENRICH/100.0)*U238 + N14)
C
          NDUNAT = NDUN
          NDN14  = NDUN
          NDU235 = NDUN*ENRICH/100.0
          NDU238 = NDUN*(1.0 - ENRICH/100.0)
C
C         NOW FIND THE MACRO-ABSORPTION CROSS SECTION OF THE FUEL
```

```
C                       ABSORPTION = CAPTURE + FISSION
C
            EAF = NDN14*ABSN14 + NDU235*(CAPU235 + FISU235) +
     +            NDU238*CAPU238
C
C           NOW FIND THE MACRO-TRANSPORT CROSS SECTION OF THE FUEL
C                 TRANSPORT = SUMMATION OF SCATTER*(1-2/(3A))
C
            ETRF = NDN14*SCATN14*(1.0 - 2.0/(3.0*N14)) +
     +             NDUNAT*SCATUNAT*(1.0 - 2.0/(3.0*UNAT))
C
C           NOW FIND THE SQUARE OF THE DIFFUSION LENGHT. PROCEED TO TAKE
C            SQUARE ROOT AND THEN FIND THE INVERSE.
C
            X   = 1.0/(3.0*ETRF*EAF)
            L   = SQRT(X)
            KUN = 1.0/L
C
          RETURN
          END
C
C
C
          REAL FUNCTION KUPUN(ENRICH,FTD)
                  IMPLICIT REAL (A-Z)
C
C           BELOW ARE THE CONSTANTS AND ATOMIC WEIGHTS USED IN THE
C            CALCULATION OF THE ATOMIC DENSITY WHICH WILL BE THEN USED
C            TO FIND THE INVERSE OF THE DIFFUSION LENGTH FOR A GIVEN
C            ENRICHMENT.
C
            AVO     = 6.022E23
            U235    = 235.04394
            U238    = 238.05082
            UNAT    = 238.07000
            PU239   = 239.05218
            N14     = 14.0060
C
C           THE DENSITY OF THE FUEL IS COMPUTED BY DENSITY(100%)*(%TD)
C            FUEL DENSITY IN UNITS OF G/CM**3
C
            DENSUN = (14.18)*(FTD/100.0)
C
C           BELOW ARE THE NECESSARY CROSS SECTIONS OF THE UN FUEL
C
            CAPU235  = 101.0E-24
            CAPU238  = 2.730E-24
            FISU235  = 577.0E-24
            SCATUNAT = 8.300E-24
            FISPU239 = 741.0E-24
            ABSPU239 = 1015.E-24
            SCATPU239= 9.600E-24
            SCATN14  = 10.00E-24
            ABSN14   = 1.880E-24
C
C           THIS SECTION FINDS THE NUMBER DENSITY (ND) OF UN AND
C            FROM THIS THE INDIVIDUAL NUMBER DENSITIES OF THE
C            CONSTITUENTS.
C
            NDUN = (DENSUN*AVO)/((U235*ENRICH/100.0 +
     +             (1.0 - ENRICH/100.0)*U238)*0.8 + 0.2*PU239 + N14)
C
            NDUNAT  = NDUN
            NDN14   = NDUN
            NDU235  = NDUN*0.8*ENRICH/100.0
            NDU238  = NDUN*0.8*(1.0 - ENRICH/100.0)
            NDPU239 = NDUN*0.2
C
C           NOW FIND THE MACRO-ABSORPTION CROSS SECTION OF THE FUEL
C                       ABSORPTION = CAPTURE + FISSION
C
            EAF = NDN14*ABSN14 + NDU235*(CAPU235 + FISU235) +
     +            NDU238*CAPU238 + NDPU239*ABSPU239
C
C           NOW FIND THE MACRO-TRANSPORT CROSS SECTION OF THE FUEL
C                 TRANSPORT = SUMMATION OF SCATTER*(1-2/(3A))
C
            ETRF = NDN14*SCATN14*(1.0 - 2.0/(3.0*N14)) +
     +             NDUNAT*SCATUNAT*(1.0 - 2.0/(3.0*UNAT)) +
     +             NDPU239*SCATPU239*(1.0 - 2.0/(3.0*PU239))
```

```
C
C         NOW FIND THE SQUARE OF THE DIFFUSION LENGHT. PROCEED TO TAKE
C          SQUARE ROOT AND THEN FIND THE INVERSE.
C
          X   = 1.0/(3.0*ETRF*EAF)
          L   = SQRT(X)
          KUPUN = 1.0/L
C
        RETURN
        END
C
C
C
C       ********************
C       THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY OF THE FUEL
C        AT THE FUEL OUTER FUEL SURFACE AND USES THIS NUMBER FOR THE
C        TEMPERATURE DROP ACROSS THE GAP WITH THE GAP FORMULATIONS.
C
        REAL FUNCTION KFGAP(FTYPE,TFS,FTD)
                IMPLICIT REAL (A-Z)
C
C       MATERIAL: UN (MONONITRIDE 400<T<2100 K) REF: ANL-AFP-27
C        *TEMPERATURE MUST BE IN DEGREES KELVIN (K)
C
          IF (FTYPE.EQ.0.0) THEN
            CC = (1.0 - (1.0 - FTD/100.0))/(1.0 + 0.5*(1.0 - FTD/100.0))
C
            KFGAP = CC*(4.63 + 2.32E-2*TFS - 5.96E-6*TFS**2.0)/100.0
          ENDIF
C
C       MATERIAL: UPUN (MIXNITRIDE 400<T<1900 K) REF: ANL-AFP-27
C        *TEMPERATURE MUST BE IN DEGREES KELVIN (K)
C
          IF (FTYPE.EQ.1.0) THEN
            CC = (1.0 - (1.0 - FTD/100.0))/(1.0 + (1.0 - FTD/100.0))
C
            KFGAP = CC*(10.297 + 9.538E-3*TFS - 1.484E-6*TFS**2.0)/100.0
          ENDIF
C
        RETURN
        END
C
C
C
C       ********************
C       THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY (W/CM-K)
C        FOR A PARTICULAR CLADDING AND AVERAGE CLAD TEMPERATURE.
C
        REAL FUNCTION KC(CLTYPE,TEMP)
                IMPLICIT REAL (A-Z)
C
C         MATERIAL:  NIOBIUM (Nb-1%Zr)     REF: FUNDAMENTALS OF HEAT &
C          MASS TRANSFER BY INCROPERA AND DEWITT, P. 757.
C
          IF (CLTYPE.EQ.0.0) THEN
                KC = 0.000147222*TEMP + 0.496
          ENDIF
C
C         MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: FUNDAMENTALS OF
C          HEAT & MASS TRANSFER BY INCROPERA AND DEWITT, P. 758.
C
          IF (CLTYPE.EQ.1.0) THEN
                KC = 0.00004*TEMP + 0.562
          ENDIF
C
C         MATERIAL:  SS-316 & 316L         REF: FUNDAMENTALS OF HEAT &
C          MASS TRANSFER BY INCROPERA AND DEWITT, P. 757.
C
          IF (CLTYPE.EQ.2.0) THEN
                KC = 0.000150*TEMP + 0.0925
          ENDIF
C
C         MATERIAL:  SS-304                REF: FUNDAMENTALS OF HEAT &
C          MASS TRANSFER BY INCROPERA AND DEWITT, P. 757.
C
          IF (CLTYPE.EQ.3.0) THEN
                KC = 0.000140*TEMP + 0.114
          ENDIF
C
C         MATERIAL:  W - 26% Re            REF: REFRACTORY METALS IN
```

```
C          SPACE NUCLEAR POWER BY LYNN B. LUNDBERG, P. 45. (NOTE:
C          THERMAL CONDUCTIVITY IN UNITS OF W/CM-K @ 1500 K)
C
           IF (CLTYPE.EQ.4.0) THEN
                 KC = 0.60
           ENDIF
C
         RETURN
         END
C
C
C
C        ********************
C        THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY (W/CM-K) OF THE
C         LINER CORRESPONDING TO A PARTICULAR LINER COMPOSITION AND TEMP.
C
         REAL FUNCTION KL(LITYPE,TEMP)
                 IMPLICIT REAL (A-Z)
C
C        MATERIAL: TUNGSTEN  REF: FUNDAMENTALS OF HEAT & MASS TRANSFER
C         BY INCROPERA AND DEWITT, P. 758.
C
               IF (LITYPE.EQ.0.0) THEN
C
                 IF (TEMP.LE.600.0) THEN
                         KL = -0.001225*TEMP + 2.097
                 ENDIF
C
                 IF ((TEMP.GT.600.0).AND.(TEMP.LE.1000.0)) THEN
                         KL = -0.000475*TEMP + 1.647
                 ENDIF
C
                 IF (TEMP.GT.1000.0) THEN
                         KL = -0.00018*TEMP + 1.348
                 ENDIF
C
               ENDIF
C
         RETURN
C
         END
C
C
C
C        ********************
C        THIS FUNCITON COMPUTES THE THERMAL EXPANSION COEFF. FOR
C         A PARTICULAR CLAD TYPE FOR AN AVERAGE CLAD TEMPERATURE.
C
         REAL FUNCTION EXPC(CLTYPE,TCAVG)
                 IMPLICIT REAL (A-Z)
C
C          MATERIAL:  NIOBIUM (Nb-1%Zr)    REF: MECHANICAL AND PHYSICAL
C           PROPERTIES OF REFRACTORY METALS AND ALLOYS BY J.B. CONWAY,
C           P. 231. (25<T<2500 C) NOTE: THESE EXP. COEFFS. WERE MODIFIED
C           BECAUSE THEY WERE REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C           *TEMPERATURES MUST BE IN UNITS OF CELCIUS (C)
C
           IF (CLTYPE.EQ.0.0) THEN
                 TCAVGC = TCAVG - 273.2
                 EXPC = (-4.10E-5 + 5.96E-6*TCAVGC + 1.34E-9*(TCAVGC**2.0))/
     +                  (TCAVGC - 25.0)
           ENDIF
C
C          MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: MECHANICAL AND
C           PHYSICAL PROPERTIES OF REFRACTORY METALS AND ALLOYS BY J.B. CONWAY,
C           P. 231. (25<T<2500 C) NOTE: THESE EXP. COEFFS. WERE MODIFIED
C           BECAUSE THEY WERE REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C           *TEMPERATURES MUST BE IN UNITS OF CELCIUS (C)
C
           IF (CLTYPE.EQ.1.0) THEN
                 TCAVGC = TCAVG - 273.2
                 EXPC = (-7.34E-5 + 5.36E-6*TCAVGC + 1.26E-9*(TCAVGC**2.0))/
     +                  (TCAVG - 25.0)
           ENDIF
C
C          MATERIAL:  SS-316 & 316L        REF:  SOURCE BOOK OF INDUSTRIAL
C           ALLOY AND ENGINEERING DATA, AMERICAN SOCIETY FOR METALS,
C           1978, P. 207.
C
           IF (CLTYPE.EQ.2.0) THEN
```

```
C
            IF (TCAVGC.LE.588.6) THEN
               EXPC = 8.3488E-10*TCAVG + 1.5709E-5
            ENDIF
C
            IF ((TCAVGC.GT.588.6).AND.(TCAVGC.LE.810.8)) THEN
               EXPC = 5.6706E-9*TCAVG + 1.28623E-5
            ENDIF
C
            IF (TCAVGC.GT.810.8) THEN
               EXPC = 9.0713E-9*TCAVG + 1.0105E-5
            ENDIF
C
         ENDIF
C
C        MATERIAL:  SS-304              REF:  SOURCE BOOK OF INDUSTRIAL
C         ALLOY AND ENGINEERING DATA, AMERICAN SOCIETY FOR METALS,
C         1978, P. 206.
C
         IF (CLTYPE.EQ.3.0) THEN
               EXPC = 2.6234E-9*TCAVG + 1.6277E-5
         ENDIF
C
C        MATERIAL:  W - 26% Re          REF: MECHANICAL AND PHYSICAL
C         PROPERTIES OF REFRACTORY METALS AND ALLOYS BY J.B. CONWAY,
C         P. 231. (25<T<2500 C) NOTE: THESE EXP. COEFFS. WERE MODIFIED
C         BECAUSE THEY WERE REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C         *TEMPERATURES MUST BE IN UNITS OF CELCIUS (C)
C
         IF (CLTYPE.EQ.4.0) THEN
               TCAVGC = TCAVG - 273.2
               EXPC = (-8.46E-6 + 3.91E-6*TCAVGC + 1.14E-9*(TCAVGC**2.0))/
     +                (TCAVGC - 25.0)
         ENDIF
C
      RETURN
      END
C
C
C
C     ********************
C     THIS FUNCTION COMPUTES THE THERMAL EXPANSION COEFF. FOR
C      A PARTICULAR FUEL AND AVERAGE FUEL TEMPERATURE.
C
      REAL FUNCTION EXPF(FTYPE,TFAVG1)
            IMPLICIT REAL (A-Z)
C
C        MATERIAL: UN (MONONITRIDE 293<T<1873 K)   REF:  ANL-AFP-27
C         NOTE: THESE EXP. COEFF. WERE MODIFIED BECAUSE THEY WERE
C         REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C         *TEMPERATURES MUST BE IN UNITS OF KELVIN (K)
C
         IF (FTYPE.EQ.0.0) THEN
               EXPF = (-2.49E-3 + 7.80E-6*TFAVG1 + 1.11E-9*(TFAVG1**2.0))/
     +                (TFAVG1 - 298.2)
         ENDIF
C
C        MATERIAL: UPUN (MIXNITRIDE 298<T<1800 K)  REF:  ANL-AFP-27
C         NOTE: THESE EXP. COEFF. WERE MODIFIED BECAUSE THEY WERE
C         REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C         *TEMPERATURES MUST BE IN UNITS OF KELVIN (K)
C
         IF (FTYPE.EQ.1.0) THEN
               EXPF = (-2.26E-3 + 6.95E-6*TFAVG1 + 1.63E-9*(TFAVG1**2.0))/
     +                (TFAVG1 - 298.2)
         ENDIF
C
      RETURN
      END
C
C
C
C     ********************
C     THIS FUNCTION CALCULATES THE MEYER HARDNESS NUMBER FOR
C      VARIOUS TYPES OF CLADDING (NOTE: FOR THIS PROGRAM THE
C      MEYER'S HARDNESS NUMBER WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF CLADDING AND TREATED AS IF ONLY
C      THE MATERIAL ZIRCALOY WAS USED. REF: NUCLEAR POWER PLANT
C      ENGINEERING BY J.H. RUST, P. 298.
C      *MEYER HARDNESS NUMBERS MUST HAVE UNITS OF PSI (lbs/cm**2)
```

```
C
      REAL FUNCTION MEYERC(CLTYPE)
            IMPLICIT REAL (A-Z)
C
C       MATERIAL:  NIOBIUM (Nb-1%Zr)    REF: SEE ABOVE
C
        IF (CLTYPE.EQ.0.0) THEN
            MEYERC = 14.2E4
        ENDIF
C
C       MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: SEE ABOVE
C
        IF (CLTYPE.EQ.1.0) THEN
            MEYERC = 14.2E4
        ENDIF
C
C       MATERIAL:  SS-316 & 316L         REF: SEE ABOVE
C
        IF (CLTYPE.EQ.2.0) THEN
            MEYERC = 13.0E4
        ENDIF
C
C       MATERIAL:  SS-304                REF: SEE ABOVE
C
        IF (CLTYPE.EQ.3.0) THEN
            MEYERC = 13.0E4
        ENDIF
C
C       MATERIAL:  W - 26% Re            REF: SEE ABOVE
C
        IF (CLTYPE.EQ.4.0) THEN
            MEYERC = 14.2E4
        ENDIF
C
C
      RETURN
      END
C
C
C
C     **********************
C     THIS FUNCTION CALCULATES THE MEYER HARDNESS NUMBER FOR
C      VARIOUS TYPES OF LINERS (NOTE: FOR THIS PROGRAM THE
C      MEYER'S HARDNESS NUMBER WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF LINERS AND TREATED AS IF ONLY
C      THE MATERIAL ZIRCALOY WAS USED. REF: NUCLEAR POWER PLANT
C      ENGINEERING BY J.H. RUST, P. 298.
C      *MEYER HARDNESS NUMBERS MUST HAVE UNITS OF PSI (lbs/cm**2)
C
      REAL FUNCTION MEYERL(LITYPE)
            IMPLICIT REAL (A-Z)
C
C       MATERIAL: TUNGSTEN  REF: SEE ABOVE
C
        IF (LITYPE.EQ.0.0) THEN
            MEYERL = 14.2E4
        ENDIF
C
      RETURN
C
      END
C
C
C
C     **********************
C     THIS FUNCTION CALCULATES THE SURFACE ROUGHNESS  FOR
C      VARIOUS TYPES OF CLADDING (NOTE: FOR THIS PROGRAM THE
C      SURFACE ROUGHNESS  WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF CLADDING AND TREATED AS IF ONLY
C      THE MATERIAL ZIRCALOY WAS USED. REF: NUCLEAR POWER
C      PLANT ENGINEERING BY J.H. RUST, P. 138.
C
      REAL FUNCTION R1(CLTYPE)
            IMPLICIT REAL (A-Z)
C
C       MATERIAL:  NIOBIUM (Nb-1%Zr)     REF: SEE ABOVE
C
        IF (CLTYPE.EQ.0.0) THEN
            R1 = 0.0001524
        ENDIF
```

```
C
C       MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: SEE ABOVE
C
        IF (CLTYPE.EQ.1.0) THEN
              R1 = 0.0001524
        ENDIF
C
C       MATERIAL:  SS-316 & 316L          REF: SEE ABOVE
C
        IF (CLTYPE.EQ.2.0) THEN
              R1 = 0.0001524
        ENDIF
C
C       MATERIAL:  SS-304                 REF: SEE ABOVE
C
        IF (CLTYPE.EQ.3.0) THEN
              R1 = 0.0001524
        ENDIF
C
C       MATERIAL:  W - 26% Re             REF: SEE ABOVE
C
        IF (CLTYPE.EQ.4.0) THEN
              R1 = 0.0001524
        ENDIF
C
      RETURN
      END
C
C
C
C     ********************
C     THIS FUNCTION CALCULATES THE SURFACE ROUGHNESS  FOR
C      VARIOUS TYPES OF FUEL COMPOSITIONS (NOTE: FOR THIS PROGRAM
C      THE SURFACE ROUGHNESS  WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF COMPOSITION AND TREATED AS IF ONLY
C      THE FUEL MATERIAL WAS ZIRCALOY. REF: NUCLEAR POWER PLANT
C      ENGINEERING BY J.H. RUST, P. 138.
C
      REAL FUNCTION R2(FTYPE)
              IMPLICIT REAL (A-Z)
C
C     MATERIAL: UN (MONONITRIDE) REF: SEE ABOVE
C
        IF (FTYPE.EQ.0.0) THEN
              R2 = 0.0001524
        ENDIF
C
C     MATERIAL: UPUN (MIXNITRIDE) REF: SEE ABOVE
C
        IF (FTYPE.EQ.1.0) THEN
              R2 = 0.0001524
        ENDIF
C
      RETURN
      END
C
C
C
C     ********************
C     THIS FUNCTION CALCULATES THE SURFACE ROUGHNESS  FOR
C      VARIOUS TYPES OF LINER COMPOSITIONS (NOTE: FOR THIS PROGRAM
C      THE SURFACE ROUGHNESS  WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF COMPOSITION AND TREATED AS IF ONLY
C      THE FUEL MATERIAL WAS ZIRCALOY. REF: NUCLEAR POWER PLANT
C      ENGINEERING BY J.H. RUST, P. 138.
C
      REAL FUNCTION R3(LITYPE)
              IMPLICIT REAL (A-Z)
C
C       MATERIAL: TUNGSTEN  REF: SEE ABOVE
C
        IF (LITYPE.EQ.0.0) THEN
              R3 = 0.0001524
        ENDIF
C
      RETURN
C
      END
      REAL FUNCTION BSIO(V)
              IMPLICIT REAL (A-Z)
```

```
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [I] OF THE FIRST KIND
C          OF ORDER ZERO;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GE.-3.75).AND.(V.LE.3.75)) THEN
              T = V/3.75
              BSIO = 1 + 3.51562*(T**2) + 3.08994*(T**4) +
     +         1.20674*(T**6) + 0.26597*(T**8) +
     +         0.03607*(T**10) + 0.00458*(T**12)
      ELSE
              T = V/3.75
              BSIO = (0.39894 + 0.01328*(T**-1) + 0.00225*(T**-2) -
     +         0.00157*(T**-3) + 0.00916*(T**-4) - 0.02057*(T**-5) +
     +         0.02635*(T**-6) - 0.01647*(T**-7) + 0.00392*(T**-8))/
     +         (SQRT(V)*EXP(-V))
      ENDIF
C
      RETURN
      END
C
C
C
      REAL FUNCTION BSI1(V)
              IMPLICIT REAL (A-Z)
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [I] OF THE FIRST KIND
C          OF ORDER ONE;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GE.-3.75).AND.(V.LE.3.75)) THEN
              T = V/3.75
              BSI1 = (0.5 + 0.87890*(T**2) + 0.51498*(T**4) +
     +         0.15084*(T**6) + 0.02658*(T**8) + 0.00301*(T**10) +
     +         0.00032*(T**12))/(V**-1)
      ELSE
              T = V/3.75
              BSI1 = (0.39894 - 0.03988*(T**-1) - 0.00362*(T**-2) +
     +         0.00163*(T**-3) - 0.01031*(T**-4) + 0.02282*(T**-5) -
     +         0.02895*(T**-6) + 0.01787*(T**-7) - 0.00420*(T**-8))/
     +         (SQRT(V)*EXP(-V))
      ENDIF
C
      RETURN
      END
C
C
      REAL FUNCTION BSKO(V)
              IMPLICIT REAL (A-Z)
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [K]OF THE FIRST KIND
C          OF ORDER ZERO;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GT.0.0).AND.(V.LE.2.0)) THEN
              T = V/2
              BIOR = BSIO(V)
              BSKO = (-ALOG(T)*BIOR) - 0.57721 + 0.42278*(T**2) +
     +         0.23069*(T**4) + 0.03488*(T**6) + 0.00262*(T**8) +
     +         0.00010*(T**10) + 0.00000740*(T**12)
      ELSE
              T = 2/V
              BSKO = (1.25331 - 0.07832*T + 0.02189*(T**2) -
     +         0.01062*(T**3) + 0.00587*(T**4) - 0.00251*(T**5) +
     +         0.00053*(T**6))/(SQRT(V)*EXP(V))
      ENDIF
C
      RETURN
      END
C
C
C
      REAL FUNCTION BSK1(V)
              IMPLICIT REAL (A-Z)
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [K]OF THE FIRST KIND
```

```
C          OF ORDER ONE;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GT.0.0).AND.(V.LE.2.0)) THEN
            T = V/2
            BI1R = BSI1(V)
            BSK1 = (V*ALOG(T)*BI1R + 1.0 + 0.15443*(T**2) -
     +       0.67278*(T**4) - 0.18156*(T**6) - 0.01919*(T**8) -
     +       0.00110*(T**10) - 0.00004*(T**12))/V
      ELSE
            T = 2/V
            BSK1 = (1.25331 + 0.23498*(T) - 0.03655*(T**2) +
     +       0.01504*(T**3) - 0.00780*(T**4) + 0.00325*(T**5) -
     +       0.00068*(T**6))/(SQRT(V)*EXP(V))
      ENDIF
C
      RETURN
      END
```

```
                        PROGRAM TDC1MOD2
C
C       .........performed by DANIEL E. BROZAK - Feb. 1987........
C                          a.k.a. """ WILDMAN """
C
C       THIS PROGRAM WAS WRITTEN IN ONE DAY FOR THE CALCULATION OF
C        CLAD AND FUEL TEMPERATURES AT A GIVEN AXIAL LOCATION.  THIS
C        PROCEDURE STARTS WITH THE CLADDING OUTER SURFACE TEM-
C        PERATURE AND WORKS INWARD TOWARDS THE FUEL CENTERLINE.
C        THE ROSS AND STOUTE GAP CONDUCTANCE MODEL IS EMPLOYED.
C
C       LISTED BELOW ARE THE DESIGN PARAMETERS USED THROUGHOUT
C        THIS PROGRAM ALONG WITH THEIR FUNCTION DESCRIPTIONS.
C        NOTE: THE INPUT TEMPERATURES MUST BE IN KELVIN !!!!!
C
C       IDENT    > PIN IDENTIFICATION STRING
C       RFO      > FUEL OUTER RADIUS (CM)
C       RFI      > FUEL INNER RADIUS IF ANNULAR (CM)
C       RCO      > CLAD OUTER RADIUS (CM)
C       RCI      > CLAD INNER RADIUS (CM)
C       TFS      > FUEL SURFACE TEMPERATURE (K)
C       TFCL     > FUEL CENTERLINE TEMPERATURE (K)
C       TFRAD    > FUEL TEMPERATURE AT THAT PARTICULAR RADIUS (K)
C       TFAVG    > FUEL AVERAGE TEMPERATURE AT PEAK AXIAL LOCATION (K)
C       TFAVGVOL> AREA AVERAGE TEMPERATURE AT PEAK AXIAL LOCATION (K)
C       TCO      > CLAD OUTER SURFACE TEMPERATURE (K)
C       TCI      > CLAD INNER SURFACE TEMPERATURE (K)
C       TCAVG    > CLAD AVERAGE TEMPERATURE (K)
C       TLO      > LINER OUTER SURFACE TEMPERATURE (K)
C       TLI      > LINER INNER SURFACE TEMPERATURE (K)
C       CLTHCK   > CLADDING THICKNESS (CM)
C       LITHCK   > LINER THICKNESS (CM)
C       Q3TAVG   > TOTAL AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                  AT THE GIVEN AXIAL LOCATION (W/CM**3)
C       Q3FAVG   > AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                  OF THE FUEL (W/CM**3)
C       Q3CAVG   > FRACTION OF THE AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                  FOR GAMMA HEATING WITHIN THE CLADDING (W/CM**3)
C       Q3LAVG   > FRACTION OF THE AVERAGE VOLUMETRIC HEAT GENERATION RATE
C                  FOR GAMMA HEATING WITHIN THE LINER (W/CM**3)
C       ALPHAC   > THERMAL EXPANSION COEFFICIENT FOR THE CLADDING (K**-1)
C       ALPHAF   > THERMAL EXPANSION COEFFICIENT FOR THE FUEL (K**-1)
C       GAPCOLD  > GAP WIDTH AT COLD CONDITIONS (CM)
C       GAPHOT   > GAP WIDTH AT HOT CONDITIONS (CM)
C       GAPTYPE  > TYPE OF BONDING USED IN THE FUEL-CLAD TYPE
C       CLTYPE   > TYPE OF CLADDING
C       FTD      > FUEL THEORETICAL DENSITY
C       ENRICH   > ENRICHMENT OF U-235 IN FUEL PELLET
C       GEOM     > SOLID OR ANNULAR FUEL PELLET
C       FLUX     > THERMAL OR FAST FLUX EXPERIENCED BY FUEL ROD
C       FTYPE    > FUEL COMPOSITION -MONO OR MIXED
C       LITYPE   > LINER COMPOSITION
C       CONV     > CONVERGENCE LIMIT USED IN CRITERIA TESTS
C       PERCCL   > PERCENTAGE OF HEATING IN CLADDING
C       PERCLI   > PERCENTAGE OF HEATING IN LINER
C
C
C       ..........................................................
C       ..........................................................
C       ..........................................................
C       ..........................................................
C       ..........................................................
C
C
C       LISTED BELOW IS A DESCRIPTION OF THE INPUT DECK - EACH
C        VARIABLE IS LISTED ON A SEPARATE LINE.  A BRIEF [NOTE]
C        WILL BE GIVEN TO EACH VARIABLE IF NEEDED.  BE SURE THAT
C        UNITS ARE CORRECT AS DESCRIBED IN PREVIOUS SECTION.
C
C       ROW 0  - NUMPIN [number of pins represented in data deck-
C                enter only once as first line in data deck]
C       ROW 1  - IDENT [maximum 20 character string]
C       ROW 2  - RFO (cm)
C       ROW 3  - RFI (cm) [a zero must be entered if pellet is solid]
C       ROW 4  - RCO (cm)
C       ROW 5  - TCO (K)
C       ROW 6  - CLTHCK (cm)
C       ROW 7  - LITHCK (cm) [a zero must be entered if no liner exists]
C       ROW 8  - Q3TAVG (W/cm**3)
C       ROW 9  - CLTYPE [0 > Nb, 1 > Ta, 2 > SS316, 3 > SS304, 4 > W-Re]
```

```
C       ROW 10 - GEOM [0 > solid, 1 > annular]
C       ROW 11 - GAPTYPE [0 > helium, 1 > sodium, 2 > lithium]
C       ROW 12 - GAPCOLD (cm)
C       ROW 13 - FTD (%)
C       ROW 14 - ENRICH (%)
C       ROW 15 - FLUX [0 > thermal, 1 > fast]
C       ROW 16 - FTYPE [0 > mono, 1 > mixed]
C       ROW 17 - LITYPE [0 > tungsten]
C       ROW 18 - CONV
C       ROW 19 - PERCCL [number is not in % format]
C       ROW 20 - PERCLI [number is not in % format]
C
C
C       THIS IS AN EXAMPLE OF AN INPUT DECK
C
C
C       ROW 0  - 1
C       ROW 1  - ORR UN3-B
C       ROW 2  - 0.3810
C       ROW 3  - 0.0
C       ROW 4  - 0.4620
C       ROW 5  - 1673
C       ROW 6  - 0.069
C       ROW 7  - 0.00762
C       ROW 8  - 632.13
C       ROW 9  - 1.0
C       ROW 10 - 0.0
C       ROW 11 - 0.0
C       ROW 12 - 0.0051
C       ROW 13 - 95.0
C       ROW 14 - 12.9
C       ROW 15 - 0.0
C       ROW 16 - 0.0
C       ROW 17 - 0.0
C       ROW 18 - 0.001
C       ROW 19 - 0.04
C       ROW 20 - 0.01
C
C
C       ..........................................................
C       ..........................................................
C       ..........................................................
C       ..........................................................
C       ..........................................................
C
C
        IMPLICIT REAL*4 (A-Z)
        INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
        REAL Q,Q1
C
        DIMENSION TRADPT1(100),TRADPT2(100)
C
        COMMON/C/TCO,RCO,PERCLI,PERCCL,CLTHCK
        COMMON/G/TCI,TCAVG,GAPCOLD,TLI,GAPTYPE,TP,ITERG
        COMMON/F/GEOM,FLUX,ENRICH,RFI,ITERF
        COMMON/CandG/LITHCK,CLTYPE,LITYPE
        COMMON/GandF/FTD,Q3FAVG,FTYPE,Q,Q1
        COMMON/CandF/Q3TAVG
        COMMON/CandGandF/RFO,CONV
C
        CHARACTER IDENT*20
C
        OPEN (UNIT=1,FILE='TEMPI.DAT',STATUS='OLD')
        OPEN (UNIT=6,FILE='TEMPO.DAT',STATUS='UNKNOWN')
C
C       THESE PARAMETERS ARE USED FOR THE NUMBER OF NODE POINTS ACROSS
C        THE RADIUS IN WHICH THE FUEL TEMPERATURE DISTRIBUTION WILL
C        BE CALCULATED AND NDEG IS USED WITHIN THE POLYNOMIAL SOLVER
C        SPECIFYING THAT IT IS A CUBIC POLYNOMIAL.
C
        Q    = 10
        Q1   = Q + 1
        NDEG = 3
C
C       READ IN THE DESIGN PARAMETERS
C
        READ (1,*) NUMPIN
C
        DO 9999 NUM = 1,NUMPIN,1
C
```

```
      READ (1,262) IDENT
      READ (1,*) RFO
      READ (1,*) RFI
      READ (1,*) RCO
      READ (1,*) TCO
      READ (1,*) CLTHCK
      READ (1,*) LITHCK
      READ (1,*) Q3TAVG
      READ (1,*) CLTYPE
      READ (1,*) GEOM
      READ (1,*) GAPTYPE
      READ (1,*) GAPCOLD
      READ (1,*) FTD
      READ (1,*) ENRICH
      READ (1,*) FLUX
      READ (1,*) FTYPE
      READ (1,*) LITYPE
      READ (1,*) CONV
      READ (1,*) PERCCL
      READ (1,*) PERCLI
C
C
 262   FORMAT (A20)
      WRITE (6,101) IDENT
 101   FORMAT (///,5X,A20)
      WRITE (6,100) RFO
 100   FORMAT (5X,'RFO          > ',F8.5,' (CM)')
      WRITE (6,103) RFI
 103   FORMAT (5X,'RFI         > ',F8.5,' (CM)')
      WRITE (6,99) RCO
 99    FORMAT (5X,'RCO          > ',F8.5,' (CM)')
      WRITE (6,98) TCO
 98    FORMAT (5X,'TCO          > ',F8.2,' (K)')
      WRITE (6,97) CLTHCK
 97    FORMAT (5X,'CLTHCK       > ',F8.5,' (CM)')
      WRITE (6,96) LITHCK
 96    FORMAT (5X,'LITHCK       > ',F8.5,' (CM)')
      WRITE (6,95) Q3TAVG
 95    FORMAT (5X,'Q3TAVG       > ',F8.2,' (W/CM**3)')
      WRITE (6,92) CLTYPE
 92    FORMAT (5X,'CLTYPE       > ',F3.1)
      WRITE (6,91) GEOM
 91    FORMAT (5X,'GEOM         > ',F3.1)
      WRITE (6,90) GAPTYPE
 90    FORMAT (5X,'GAPTYPE      > ',F3.1)
      WRITE (6,89) GAPCOLD
 89    FORMAT (5X,'GAPCOLD      > ',F8.5)
      WRITE (6,88) FTD
 88    FORMAT (5X,'FTD         > ',F5.1)
      WRITE (6,87) ENRICH
 87    FORMAT (5X,'ENRICH       > ',F5.1)
      WRITE (6,86) FLUX
 86    FORMAT (5X,'FLUX         > ',F3.1)
      WRITE (6,85) FTYPE
 85    FORMAT (5X,'FTYPE        > ',F3.1)
      WRITE (6,876) LITYPE
 876   FORMAT (5X,'LITYPE       > ',F3.1)
      WRITE (6,102) CONV
 102   FORMAT (5X,'CONV         > ',F10.7)
      WRITE (6,94) PERCCL
 94    FORMAT (5X,'PERCCL       > ',F5.3)
      WRITE (6,93) PERCLI
 93    FORMAT (5X,'PERCLI       > ',F5.3)
C
C
C     ..............................................................
C     ..............................................................
C     ..............................................................
C     ..............................................................
C     ..............................................................
C
C
C     MAIN PROGRAM DRIVER
C
C     ----------
      CALL CLAD (TCI,TLI,TCAVG,Q3FAVG)
C     ----------
C
C     NEED TO GUESS AN AVERAGE FUEL TEMPERATURE AND SURFACE
C      TEMPERATURE CORRESPONDING TO THE PEAK AXIAL LOCATION.
```

```
C
      TFAVGVOL2 = TCI + 200.0
      TFS       = TCI + 100.0
      TP        = 298.2
      ITERG     = 0
      ITERF     = 0
C
C     NEED TO COMPUTE SOME TYPICAL VALUES FOR THE DISTRIBUTION OF
C      THE TEMPERATURE ACROSS THE FUEL RADIUS SO THAT A CRITERIA
C      TEST CAN BE EMPLOYED IN THE ROUTINES FOR COMPUTING THE SAME
C      TEMPERATURE DISTRIBUTION.
C
C
C     SET UP INITIAL FUEL TEMPERATURE PROFILE TO BE USED IN FUEL
C      ITERATIVE PROCESS.
C
      DO 967 JJ = 1,Q1,1
            TRADPT2(JJ) = TFS + 8.0*JJ
 967  CONTINUE
C
C     ----------
      CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,GAPHOT,
     +          CLOSEDGAP)
C     ----------
C
C
C     ----------
      CALL FUEL (TFS,TRADPT1,TRADPT2,TFAVGVOL2,TFAVG2,CLOSEDGAP)
C     ----------
C
 9999 CONTINUE
C
      STOP
      END
C
C
C     ..........................................................
C     ..........................................................
C     ..........................................................
C     ..........................................................
C     ..........................................................
C
C
      SUBROUTINE CLAD (TCI,TLI,TCAVG,Q3FAVG)
C
      IMPLICIT REAL*4 (A-Z)
      INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
C
      COMMON/C/TCO,RCO,PERCLI,PERCCL,CLTHCK
      COMMON/CandG/LITHCK,CLTYPE,LITYPE
      COMMON/CandF/Q3TAVG
      COMMON/CandGandF/RFO,CONV
C
C
C-------DESCRIBED BRIEFLY BELOW ARE ADDITIONAL PARAMETERS USED----------
C      ENTIRELY WITHIN THIS SUBROUTINE
C
C     TCAVG1 and TCAVG2 - USED AS PREVIOUS AND NEWLY CALCULATED
C                         AVERAGE CLADDING TEMPERATURES IN THE
C                         ITERATIVE PROCESS FOR CONVERGENCE TEST
C     TLAVG1 and TLAVG2 - USED AS PREVIOUS AND NEWLY CALCULATED
C                         AVERAGE LINER TEMPERATURES IN THE
C                         ITERATIVE PROCESS FOR CONVERGENCE TEST
C     KCLAD and KLINER - REPRESENTS THE THERMAL CONDUCTIVITY OF
C                        THE CLADDING AND LINER RESPECTIVELY
C     ESPC and ESPL - THE CONVERGENCE CRITERIA TEST
C-----------------------------------------------------------------------
C
C     THIS NEXT SECTION EMPLOYS AN ITERATIVE METHOD IN THE
C      COMPUTATION OF THE TEMPERATURE DROPS EXPERIENCED
C      ACROSS THE CLADDING AND LINER.
C
C
      RCI = RCO - CLTHCK
      RLO = RCI
      RLI = RLO - LITHCK
C
C     CALCULATE THE HEAT GENERATION IN LINER AND CLADDING
C
      IF (LITHCK.EQ.0.0) THEN
C
```

```
                PERCLI = 0.0
                Q3LAVG = 0.0
        ELSE
                Q3LAVG = PERCLI*Q3TAVG
C
        ENDIF
C
C       ASSUME AN INITIAL INNER CLADDING TEMPERATURE FOR ITERATION
C
                TCI = TCO + 40.0
C
                Q3CAVG = PERCCL*Q3TAVG
C
                Q3FAVG = (1.0 - PERCCL - PERCLI)*Q3TAVG
C
                Z = RCI/RCO
C
                TCAVG2 = (TCO + TCI)/2.0
 3              TCAVG1 = TCAVG2
C
                KCLAD = KC(CLTYPE,TCAVG1)
C
                TCI = TCO + (Q3CAVG/(2.0*KCLAD))*((RCO**2.0/2.0)*
     +                (1.0-RCI**2.0/RCO**2.0) + RCI**2.0*(ALOG(Z)*
     +                (1.0-(Q3FAVG/Q3CAVG)*(RFO**2.0/RCI**2.0))))
C
                TCAVG2 = (TCO + TCI)/2.0
                EPSC = ABS(TCAVG1 - TCAVG2)/TCAVG1
                IF (EPSC.GT.CONV) THEN
                        GO TO 3
                ELSE
                        WRITE (6,84) TCO
                        WRITE (6,83) TCI
                        WRITE (6,82) TCAVG2
                        GO TO 4
                ENDIF
C
C
 4      TCAVG = TCAVG2
C
C
C       THIS SECTION COMPUTES THE TEMPERATURE DROP ACROSS
C        THE LINER IF A LINER IS PRESENT.
C
        IF (LITHCK.EQ.0.0) THEN
C
                GO TO 6
C
        ELSE
C
                TLO = TCI
C
C       ASSUME AN INITIAL INNER LINER TEMPERATURE FOR ITERATION
C
                TLI = TCI + 4.0
C
                Z = RLI/RLO
C
                TLAVG2 = (TLO + TLI)/2.0
 5              TLAVG1 = TLAVG2
C
C       THIS NEXT FUNCTION COMPUTES THE CONDUCTIVITY OF THE LINER
C        (WATTS/CM*K) FOR TUNGSTEN USING THE AVERAGE LINER TEMP.
C
                KLINER = KL(LITYPE,TLAVG1)
C
                TLI = TLO + (Q3LAVG/(2.0*KLINER))*((RLO**2.0/2.0)*
     +                (1.0-RLI**2.0/RLO**2.0) + RLI**2.0*(ALOG(Z)*
     +                (1.0-(Q3FAVG/Q3LAVG)*(RFO**2.0/RLI**2.0))))
C
                TLAVG2 = (TLO + TLI)/2.0
                EPSL = ABS(TLAVG1 - TLAVG2)/TLAVG1
                IF (EPSL.GT.CONV) THEN
                        GO TO 5
                ELSE
                        WRITE (6,81) TLO
                        WRITE (6,80) TLI
                        WRITE (6,79) TLAVG2
                        GO TO 6
                ENDIF
```

```
      ENDIF
C
 84   FORMAT (/,5X,'CLAD OUTER TEMP.  > ',F8.2,' K')
 83   FORMAT (5X,'CLAD INNER TEMP.    > ',F8.2,' K')
 82   FORMAT (5X,'CLAD AVG. TEMP.     > ',F8.2,' K')
 81   FORMAT (/,5X,'LINER OUTER TEMP. > ',F8.2,' K')
 80   FORMAT (5X,'LINER INNER TEMP.   > ',F8.2,' K')
 79   FORMAT (5X,'LINER AVG. TEMP.    > ',F8.2,' K')
C
 6    CONTINUE
C
      RETURN
      END
C
C
C     ..................................................
C     ..................................................
C     ..................................................
C     ..................................................
C     ..................................................
C
C
      SUBROUTINE GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,GAPHOT,
     +                CLOSEDGAP)
C
      IMPLICIT REAL*4 (A-Z)
      INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
C
      DIMENSION TRADPT1(100),TRADPT2(100)
C
      COMMON/G/TCI,TCAVG,GAPCOLD,TLI,GAPTYPE,TP,ITERG
      COMMON/CandG/LITHCK,CLTYPE,LITYPE
      COMMON/GandF/FTD,Q3FAVG,FTYPE,Q,Q1
      COMMON/CandGandF/RFO,CONV
C
C
C-------DESCRIBED BRIEFLY BELOW ARE ADDITIONAL PARAMETERS USED----------
C       WITHIN THIS SUBROUTINE
C
C       TFAVG1 - AVERAGE FUEL TEMPERATURE
C       ALPHAC and ALPHAF - THERMAL EXPANSION COEFFICIENTS FOR
C                           CLADDING AND FUEL RESPECTIVELY
C       GAPHOT - CALCULATED GAP WIDTH AT "HOT" CONDITION DERIVED
C                SOLELY FORM THERMAL EXPANSION OF CLAD AND FUEL
C       R1CLAD, R2FUEL and R3LINER - REFER TO RESPECTIVE SURFACE
C                                    ROUGHNESSES
C       TGAVG1 and TGAVG2 - USED AS PREVIOUS AND NEWLY CALCULATED
C                           AVERAGE CLADDING TEMPERATURES IN THE
C                           ITERATIVE PROCESS FOR CONVERGENCE TEST
C       EPS - CONVERGENCE CRITERIA TEST
C-----------------------------------------------------------------------
C
 13   DO 767 LL = 1,Q1,1
           TRADPT1(LL) = TRADPT2(LL)
 767  CONTINUE
C
      ITERF  = ITERF + 1
C
      TFAVG1 = TFAVGVOL2
C
      ALPHAC = EXPC(CLTYPE,TCAVG)
C
      ALPHAF = EXPF(FTYPE,TFAVG1)
C
C
C       NEED TO COMPUTE THE HOT GAP WIDTH CORRESPONDING TO THIS
C        AVERAGE FUEL TEMPERATURE AND THE ITERATIVE AVERAGED
C        CLAD TEMPERATURE CALCULATED IN THE PREVIOUS SECTION.
C
C
      GAPHOT = (RFO + GAPCOLD)*(1.0 + ALPHAC*(TCAVG - TP))
     +          - RFO*(1.0 + ALPHAF*(TFAVG1 - TP))
C
C       SET UP FLAG TO DETERMINE WHETHER GAP IS CLOSED OR OPEN:
C        CLOSEDGAP = 1.0 = OPEN; CLOSEDGAP = 0.0 = CLOSED
C
      CLOSEDGAP = 1.0
C
C       CALCULATE MEAN GAP THICKNESS CORRESPONDING TO SURFACE ROUGHNESS
C
```

```
            IF (LITHCK.EQ.0.0) THEN
              R1CLAD    = R1(CLTYPE)
              R2FUEL    = R2(FTYPE)
              MEAN      = (R1CLAD**2.0 + R2FUEL**2.0)/2.0
              MEANGAP = SQRT(MEAN)
            ELSE
              R2FUEL    = R2(FTYPE)
              R3LINER   = R3(LITYPE)
              MEAN      = (R2FUEL**2.0 + R3LINER**2.0)/2.0
              MEANGAP = SQRT(MEAN)
            ENDIF
C
C       SET UP NEW GAP FLAG IF GAPHOT IS LESS THAN MEANGAP.
C
            IF (GAPHOT.LE.MEANGAP) THEN
C
              GAPHOT = MEANGAP
C
              CLOSEDGAP = 0.0
C
            ENDIF
C
C
C
C       THESE SECTIONS CALCULATE THE TEMP DROP ACROSS THE HOT
C        GAP WIDTH UNDER CERTAIN FUEL GEOMETRIES AND BONDING
C        MATERIAL.  IF GAPTYPE = 0  > HELIUM, IF GAPTYPE = 1
C        > SODIUM,  ALL KGAP'S ARE IN UNITS OF WATTS/CM*K
C        NOW DETERMINE THE PRESSURE INCREASE USING THE IDEAL GAS
C        LAW RELATIONSHIP P1/T1 = P2/T2
C
C       THIS NEXT SECTION COMPUTES THE GAP CONDUCTIVITY FOR THE GAS
C        AND CONTACT POINTS(SEE NOTE) WHEN GAP CLOSURE HAS BEEN REACHED.
C        BELOW IS A SUMMARY OF THE FORMULAS USED IN THIS CALCULATION.
C        IN SELECTION OF THESE FORMULAS PRESSURE WAS TO BE INDEPENDENT
C        AS POSSIBLE BECAUSE APPROACH IS NOT A MECHANICAL ANALYSIS.
C
C        REF: FOR H(GAS)-FUNDAMENTAL ASPECTS OF NUCLEAR REACTOR FUEL
C        ELEMENTS BY D.R. OLANDER, P. 136.
C
C        REF: FOR H(SOLID)-REVIEW OF METHODS APPLICABLE TO THE CAL-
C        CULATION OF GAP CONDUCTANCE IN ZIRCALOY-CLAD UO2 FUEL RODS
C        BY D.D. LANNING AND C.R. HANN, BNWL-1894 UC-78B, P. 14.
C        ----------------------NOTE-----------------------------
C        THIS PROGRAM DOES NOT COMPUTE H(SOLID) IF CONTACT BETWEEN
C        CLADDING AND FUEL OCCURS BECAUSE OF ITS INABILITY TO COMPUTE
C        THE INTERFACIAL PRESSURE.  HOWEVER THIS FORMULA WAS STILL
C        PROGRAMMED WITH COMMENTS(NOTED BY "CC") WITHIN THE CODE IN
C        THE EVENT THAT THE CONTACT PRESSURE COULD BE DETERMINED.
C
C        THE ACCOMMODATION COEFFICIENTS WERE REFERENCED FROM THERMAL
C        ANALYSIS OF PRESSURIZED WATER REACTORS BY L.S. TONG AND
C        J. WEISMAN, P. 99.  ALSO THIS REFERENCE PROVIDES A GRAPH
C        FOR A QUICK CHECK ON THE TOTAL HEAT TRANSFER COEFF. FOR A
C        PARTICULAR GAP WIDTH, P. 98. FUNDAMENTAL ASPECTS OF NUCLEAR
C        REACTOR FUEL ELEMENTS, D.R. OLANDER, P. 138. ALSO GAP
C        CONDUCTANCE IN ZIRCALOY-CLAD LWR FUEL RODS, J.B. AINSCOUGH,
C        P. 9 & 20, ND-R-699(S)
C
C       H = H(GAS) + H(SOLID)
C
C       H(GAS) = K(GAS)/(D + G1 +G2) WHERE
C         K(GAS) > CONDUCTIVITY OF THE GAS MIXTURE (W/CM-C)
C         D      > ACTUAL FUEL-CLAD GAP DIMENSION (CM)
C         G1-G2  > TEMPERATURE JUMP DISTANCES OF FUEL & CLAD (CM)
C
C         THE JUMP DISTANCES ARE COMPUTED USING THIS CORRELATION
C          FROM THE GAPCON EQUATION
C
C         G1 = G2 = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
C     +               LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
C         ACC     > THERMAL ACCOMMODATION COEFF. FOR THE GAS & SURFACE
C         GAMMA   > Cp/Cv = 5/3 FOR MONOATOMIC GASES (NO UNITS)
C         LAMDAHe > MEAN FREE PATH AT 1 ATM. AND DEGREE CELCIUS (ATM-CM)
C         TGAVG1  > AVERAGE TEMPERATURE IN DEGREE KELVIN (K)
C         PR      > PRANDTL NUMBER 0.70 (NO UNITS)
C         P2      > PRESSURE IN ATMOSPHERES
C
CC      H(SOLID) = 1.189*2*K1*K2*PA/(H*(K1 + K2)*(R1**2 + R2**2)**.25)
```

```
CC
CC        K1    > THERMAL COND. OF CLAD AT INNER SURFACE TEMP. (W/CM-C)
CC        K2    > THERMAL COND. OF FUEL AT SURFACE TEMP. (W/CM-C)
CC        PA    > THE APPARENT INTERFACIAL PRESSURE (PSI)
CC        H     > THE MEYER HARDNESS OF THE SOFTER MATERIAL (PSI)
CC        R1    > MEAN ROUGHNESS OF THE CLAD (CM)
CC        R2    > MEAN ROUGHNESS OF THE FUEL (CM)
C
C       ****************************************************************
C
        IF ((GAPTYPE.EQ.0.0).AND.(LITHCK.EQ.0.0)) THEN
C
                P1 = 14.7
                T1 = 298.2
C
 8              TGAVG1 = (TFS + TCI)/2.0
C
                ITERG = ITERG + 1
C
C         THE HELIUM CONDUCTIVITY WAS REFERENCED FROM CRC HANDBOOK
C          OF CHEMISTRY AND PHYSICS 66TH EDITION, P. E-3.
C
                IF (TGAVG1.LE.1000.0) THEN
                      KGAPHE = 0.000003032*TGAVG1 + 0.000631
                ELSE
                      KGAPHE = 0.000002507*TGAVG1 + 0.001167
                ENDIF
C
C
                P2 = P1*(TGAVG1)/(T1)
C
                   ACC = 0.425 - 2.3E-4*TGAVG1
                     IF (ACC.LT.0.08) THEN
                           ACC = 0.08
                     ENDIF
C
                   GAMMA   = 5.0/3.0
                   PR      = 0.70
                   LAMDAHe = 1.74E-5
C
CC        FOR THE CASE OF H(SOLID):
CC
CC                 PA      = P2
CC                 HMEYERC = MEYERC(CLTYPE)
CC
CC                 KTCI    = KC(CLTYPE,TCI)
CC
CC                 KTFS    = KFGAP(FTYPE,TFS,FTD)
CC
CC                 R1CLAD  = R1(CLTYPE)
CC                 R2FUEL  = R2(FTYPE)
C
C
C
                   IF (CLOSEDGAP.EQ.0.0) THEN
C
                      G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                    LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
                      HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
CC        IF CLOSEDGAP = 0.0 THEN CONTACT HAS TAKEN PLACE AND THE
CC        H(SOLID) WOULD HAVE BEEN COMPUTED BELOW.  HOWEVER THIS
CC        CANNOT BE DETERMINED BECAUSE OF THE INABILITY TO COMPUTE
CC        THE INTERFACIAL PRESSURE.  THEREFORE ONLY H(GAS) WILL BE
CC        EMPLOYED.
CC
CC                    HSOL = 1.189*2.0*KTCI*KTFS*PA/
CC     +                     (HMEYERC*(R1CLAD**2.0 + R2FUEL**2.0)**0.25*
CC      +                     (KTCI + KTFS))
CC
CC                    HGAP = HGAS + HSOL
C
                      HGAP = HGAS
C
                   ELSE
C
                      G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                    LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
```

```
                  HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
                  HGAP = HGAS
C
               ENDIF
C
C              ------------------------------------------
               Q2FAVG = Q3FAVG*RFO/2.0
C
               TFS = Q2FAVG/HGAP + TCI
C
               TGAVG2 = (TFS + TCI)/2.0
C
               EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
               IF (EPS.GT.CONV) THEN
                       P1 = P2
                       T1 = TGAVG1
C
                       GO TO 8
               ELSE
                       GO TO 12
               ENDIF
C
         ENDIF
C
C        ******************************************************************
C
         IF ((GAPTYPE.EQ.0.0).AND.(LITHCK.GT.0.0)) THEN
C
               P1 = 14.7
               T1 = 298.2
C
 9             TGAVG1 = (TFS + TLI)/2.0
C
               ITERG = ITERG + 1
C
C
C          THE HELIUM CONDUCTIVITY WAS REFERENCED FROM CRC HANDBOOK
C           OF CHEMISTRY AND PHYSICS 66TH EDITION, P. E-3.
C
               IF (TGAVG1.LE.727.0) THEN
                       KGAPHE = 0.000003032*TGAVG1 + 0.000631
               ELSE
                       KGAPHE = 0.000002507*TGAVG1 + 0.001167
               ENDIF
C
               P2 = P1*(TGAVG1)/(T1)
C
                  ACC = 0.425 - 2.3E-4*TGAVG1
                    IF (ACC.LT.0.08) THEN
                          ACC = 0.08
                    ENDIF
C
                  GAMMA    = 5.0/3.0
                  PR       = 0.70
                  LAMDAHe = 1.74E-5
C
CC        FOR THE GAS OF H(SOLID)
CC
CC                PA       = P2
CC                HMEYERL = MEYERL(LITYPE)
CC
CC                KTLI     = KL(LITYPE,TLI)
CC
CC                KTFS     = KFGAP(FTYPE,TFS,FTD)
CC
CC                R2FUEL   = R2(FTYPE)
CC                R3LINER = R3(LITYPE)
C
C
C              ------------------------------------------
               IF (CLOSEDGAP.EQ.0.0) THEN
C
                  G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
                  HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
CC        IF CLOSEDGAP = 0.0 THEN CONTACT HAS TAKEN PLACE AND THE
```

```
CC       H(SOLID) WOULD HAVE BEEN COMPUTED BELOW.  HOWEVER THIS
CC       CANNOT BE DETERMINED BECAUSE OF THE INABILITY TO COMPUTE
CC       THE INTERFACIAL PRESSURE.  THEREFORE ONLY H(GAS) WILL BE
CC       EMPLOYED.
CC
CC                  HSOL = 1.189*2.0*KTLI*KTFS*PA/
CC     +                   (HMEYERL*(R2FUEL**2.0 + R3LINER**2.0)**0.25*
CC     +                   (KTLI + KTFS))
CC
CC                  HGAP = HGAS + HSOL
C
                    HGAP = HGAS
C
                ELSE
C
                    G = 2.0*((2.0 - ACC)/ACC)*(GAMMA/(1.0 + GAMMA))*
     +                  LAMDAHe*TGAVG1/(PR*273*P2/14.7)
C
                    HGAS = KGAPHE/(GAPHOT + 2.0*G)
C
                    HGAP = HGAS
C
                ENDIF
C
C               ____________________________________________
                Q2FAVG = Q3FAVG*RFO/2.0
C
                TFS = Q2FAVG/HGAP + TLI
C
                TGAVG2 = (TFS + TLI)/2.0
C
                EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
                IF (EPS.GT.CONV) THEN
                        P1 = P2
                        T1 = TGAVG1
C
                        GO TO 9
                ELSE
                        GO TO 12
                ENDIF
C
        ENDIF
C
C       ****************************************************************
        IF (GAPTYPE.EQ.1.0) THEN
C
 10             TGAVG1 = (TFS + TCI)/2.0
C
                ITERG = ITERG + 1
C
C       THE SODIUM CONDUCTIVITY WAS REFERENCED FROM BASIC HEAT TRANSFER
C        BY M. NECATI OZISIK, P. 499.
C
                KGAPNA = -0.0004333*TGAVG1 + 1.005
C
                ZP = RFO*(1.0 + ALPHAF*(TFAVG1 - TP))
                Z  = (ZP + GAPHOT)/ZP
C
           IF (LITHCK.EQ.0.0) THEN
                TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPNA) + TCI
C
                TGAVG2 = (TFS + TCI)/2.0
           ELSE
                TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPNA) + TLI
C
                TGAVG2 = (TFS + TLI)/2.0
           ENDIF
C
                EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
                IF (EPS.GT.CONV) THEN
                        GO TO 10
                ELSE
                        GO TO 12
                ENDIF
C
        ENDIF
C
C
```

```
C       ***************************************************************
        IF (GAPTYPE.EQ.2.0) THEN
C
 15             TGAVG1 = (TFS + TCI)/2.0
C
                ITERG = ITERG + 1
C
C       THE LITHIUM CONDUCTIVITY WAS REFERENCED FROM BASIC HEAT TRANSFER
C        BY M. NECATI OZISIK, P. 504.
C
                KGAPLI = -0.02412*TGAVG1 + 55.1
C
                ZP = RFO*(1.0 + ALPHAF*(TFAVG1 - TP))
                Z  = (ZP + GAPHOT)/ZP
C
           IF (LITHCK.EQ.0.0) THEN
                TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPLI) + TCI
C
                TGAVG2 = (TFS + TCI)/2.0
           ELSE
                TFS = Q3FAVG*RFO**2.0*ALOG(Z)/(2*KGAPLI) + TLI
C
                TGAVG2 = (TFS + TLI)/2.0
           ENDIF
C
                EPS = ABS(TGAVG1 - TGAVG2)/TGAVG1
C
                IF (EPS.GT.CONV) THEN
                        GO TO 15
                ELSE
                        GO TO 12
                ENDIF
C
        ENDIF
C
 12     CONTINUE
C
        RETURN
        END
C
C       .............................................................
C       .............................................................
C       .............................................................
C       .............................................................
C       .............................................................
C
C
        SUBROUTINE FUEL (TFS,TRADPT1,TRADPT2,TFAVGVOL2,TFAVG2,CLOSEGAP)
C
        IMPLICIT REAL*4 (A-Z)
        INTEGER PT,JJ,KK,P,LL,ITERG,ITERF
C
        DIMENSION TRADPT1(100),TRADPT2(100)
C
        COMMON/F/GEOM,FLUX,ENRICH,RFI,ITERF
        COMMON/CandF/Q3TAVG
        COMMON/GandF/FTD,Q3FAVG,FTYPE,Q,Q1
        COMMON/CandGandF/RFO,CONV
C
C
C-------DESCRIBED BRIEFLY BELOW ARE ADDITIONAL PARAMETERS USED----------
C        WITHIN THIS SUBROUTINE
C
C       K - INVERSE DIFFUSION LENGTH OF CORRESPONDING FUEL
C       PP and C - USED AS PART OF INTEGRAL THERMAL CONDUCTIVITY
C                  FORMULATION
C       PART and TRAD - USED TO FIND FUEL TEMPERATURE AT PARTICULAR
C                       RADIUS POSITION DETERMINED FORM PARAMETER [I]
C-----------------------------------------------------------------------
C
C
C       THIS SECTION COMPUTES THE TEMPERATURE DISTRIBUTION ACROSS
C        THE FUEL PELLET FOR VARIOUS PELLET GEOMETRIES AND FLUXES.
C        THERE ARE TWO TYPES AND GEOMETRIES (SOLID & ANNULAR) AND
C        TWO TYPES OF FLUXES (THERMAL & FAST).  THE PARTICULAR
C        COMBINATION OF INTEREST WILL BE DETERMINED BY THE INPUT
C        DATA. NOTATION: IF GEOM = 0 > SOLID, IF GEOM = 1 > ANNULAR,
C        IF FLUX = 0 > THERMAL, IF FLUX = 1 > FAST, IF FTYPE = 0 >
C        UN (MONONITRIDE), IF FTYPE = 1 > UPuN (MIXNITRIDE)
C        ALL THE DERIVATIONS FOR THE FUEL DISTRIBUTION FORMULAS
```

```
C         WERE DERIVED AND REFERENCED IN THE ATTACHED APPENDICES.
C
C
C
C        ....................SOLID/THERMAL/MONO OR MIX.................
C
 1000    IF ((GEOM.EQ.0.0).AND.(FLUX.EQ.0.0)) THEN
C
            IF (FTYPE.EQ.0.0) THEN
                 K = KUN(ENRICH,FTD)
            ELSE
                 K = KUPUN(ENRICH,FTD)
            ENDIF
C
                 V = K*RFO
                 BI00 = BSI0(V)
                 BI10 = BSI1(V)
C
                 Q3KNOT = K*RFO*Q3FAVG/(2.0*BI10)
                 PP = 1.0 - FTD/100.0
C
                 SUMVOL = 0.0
                 SUM    = 0.0
                 PT     = 0
                 I      = RFO/Q
C
                 DO 21 RAD = 0.0,RFO,I
                    PT = PT + 1
                    V = K*RAD
                    BIOR = BSI0(V)
C
            IF (FTYPE.EQ.0.0) THEN
C
                 C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                    PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                     100.0*((Q3KNOT/K**2)*
     +                     (BI00 - BIOR))/C
C
C
C        THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C         FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C         THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C         DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C              0.91111*(T**0.45504) [BEFORE INTEGRATION]
C              (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                 TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
            ELSE
C
                 C = (1.0 - PP)/(1.0 + PP)
C
                    PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                     100.0*((Q3KNOT/K**2)*
     +                     (BI00 - BIOR))/C
C
C
C        THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C         FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C         THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C         DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C              1.74900*(T**0.34123) [BEFORE INTEGRATION]
C              (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                 TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
            ENDIF
C
                 IF (PT.EQ.1) THEN
                   TRADVOL = TRAD*(RAD + I/2.0)**2.0
                 ENDIF
                 IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                   TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                             (RAD - I/2.0)**2.0)
                 ENDIF
                 IF (PT.EQ.Q1) THEN
                   TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
```

```
                    ENDIF
C
                    SUMVOL = SUMVOL + TRADVOL
C
                    TRADPT2(PT) = TRAD
C
                    SUM = SUM + TRAD
C
 21              CONTINUE
C
C       THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C        AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
        TFAVGVOL2 = SUMVOL/RFO**2.0
        TFAVG2 = SUM/Q1
C
        DO 2001 KK = 1,Q1,1
                EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                  IF (EPSF.GT.CONV) THEN
                     CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                          GAPHOT,CLOSEDGAP)
                     GO TO 1000
                  ENDIF
 2001   CONTINUE
C
        WRITE (6,751)
 751    FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
           DO 31 P = 1,Q1,1
             WRITE (6,41) P, TRADPT2(P)
 41          FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
 31        CONTINUE
C
        WRITE (6,511) TFAVGVOL2
 511    FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
        WRITE (6,51) TFAVG2
 51     FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
        GO TO 999
C
        ENDIF
C
C
C
C
C       .....................SOLID/FAST/MONO OR MIX...................
C
 1001   IF ((GEOM.EQ.0.0).AND.(FLUX.EQ.1.0)) THEN
C
                PP = 1.0 - FTD/100.0
C
                SUMVOL = 0.0
                SUM    = 0.0
                PT     = 0
                I      = RFO/Q
C
                DO 23 RAD = 0.0,RFO,I
                   PT = PT + 1
C
           IF (FTYPE.EQ.0.0) THEN
C
                C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                   PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                     100.0*((Q3TAVG/4)*
     +                     (RFO**2.0 - RAD**2.0))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            0.91111*(T**0.45504) [BEFORE INTEGRATION]
C            (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
```

```
            ELSE
C
                 C = (1.0 - PP)/(1.0 + PP)
C
                    PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                     100.0*((Q3TAVG/4)*
     +                     (RFO**2.0 - RAD**2.0))/C
C
C
C        THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C         FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C         THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C         DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C              1.74900*(T**0.34123) [BEFORE INTEGRATION]
C              (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                    TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
            ENDIF
C
                    IF (PT.EQ.1) THEN
                      TRADVOL = TRAD*(RAD + I/2.0)**2.0
                    ENDIF
                    IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                      TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                                 (RAD - I/2.0)**2.0)
                    ENDIF
                    IF (PT.EQ.Q1) THEN
                      TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
                    ENDIF
C
                    SUMVOL = SUMVOL + TRADVOL
C
                    TRADPT2(PT) = TRAD
C
                    SUM = SUM + TRAD
C
 23              CONTINUE
C
C        THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C         AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
         TFAVGVOL2 = SUMVOL/RFO**2.0
         TFAVG2 = SUM/Q1
C
         DO 2003 KK = 1,Q1,1
                 EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                   IF (EPSF.GT.CONV) THEN
                      CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                          GAPHOT,CLOSEDGAP)
                      GO TO 1001
                   ENDIF
 2003    CONTINUE
C
         WRITE (6,753)
 753     FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
            DO 33 P = 1,Q1,1
              WRITE (6,43) P, TRADPT2(P)
 43           FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
 33         CONTINUE
C
         WRITE (6,513) TFAVGVOL2
 513     FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
         WRITE (6,53) TFAVG2
 53      FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
         GO TO 999
C
         ENDIF
C
C
C
C        ..................ANNULAR/THERMAL/MONO OR MIX.................
C
 1002    IF ((GEOM.EQ.1.0).AND.(FLUX.EQ.0.0)) THEN
C
```

```
            IF (FTYPE.EQ.0.0) THEN
                 K = KUN(ENRICH,FTD)
            ELSE
                 K = KUPUN(ENRICH,FTD)
            ENDIF
C
                 V = K*RFI
                 BIOI = BSIO(V)
                 BI1I = BSI1(V)
                 BKOI = BSKO(V)
                 BK1I = BSK1(V)
                 V = K*RFO
                 BK10 = BSK1(V)
                 BI00 = BSIO(V)
                 BI10 = BSI1(V)
                 BKOO = BSKO(V)
C
                 Q3KNOT = (Q3FAVG*(RFO**2 - RFI**2)*K)/
     +                    (2.0*RFO*(BI10 - BI1I*BK10/BK1I))
     +
C
                 PP = 1.0 - FTD/100.0
C
                 SUMVOL = 0.0
                 SUM    = 0.0
                 PT     = 0
                 I      = (RFO - RFI)/Q
C
                 DO 25 RAD = RFI,RFO,I
                    PT = PT + 1
                    V = K*RAD
                    BIOR = BSIO(V)
                    BKOR = BSKO(V)
C
            IF (FTYPE.EQ.0.0) THEN
C
                 C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                    PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                     100.0*((Q3KNOT/K**2)*
     +                     (BI00 - BIOR + BI1I/BK1I*(BKOO - BKOR)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            0.91111*(T**0.45504) [BEFORE INTEGRATION]
C            (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                 TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
            ELSE
C
                 C = (1.0 - PP)/(1.0 + PP)
C
                    PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                     100.0*((Q3KNOT/K**2)*
     +                     (BI00 - BIOR + BI1I/BK1I*(BKOO - BKOR)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            1.74900*(T**0.34123) [BEFORE INTEGRATION]
C            (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                 TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
            ENDIF
C
                 IF (PT.EQ.1) THEN
                   TRADVOL = TRAD*(RAD + I/2.0)**2.0
                 ENDIF
                 IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                   TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                             (RAD - I/2.0)**2.0)
```

```
                ENDIF
                IF (PT.EQ.Q1) THEN
                  TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
                ENDIF
C
                SUMVOL = SUMVOL + TRADVOL
C
                TRADPT2(PT) = TRAD
C
                SUM = SUM + TRAD
C
 25           CONTINUE
C
C       THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C        AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
        TFAVGVOL2 = SUMVOL/RFO**2.0
        TFAVG2 = SUM/Q1
C
        DO 2005 KK = 1,Q1,1
                EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                  IF (EPSF.GT.CONV) THEN
                     CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                          GAPHOT,CLOSEDGAP)
                     GO TO 1002
                  ENDIF
 2005   CONTINUE
C
        WRITE (6,755)
 755    FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
           DO 35 P = 1,Q1,1
             WRITE (6,45) P, TRADPT2(P)
 45          FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
 35        CONTINUE
C
        WRITE (6,515) TFAVGVOL2
 515    FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
        WRITE (6,55) TFAVG2
 55     FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
        GO TO 999
C
        ENDIF
C
C
C
C       ..................ANNULAR/FAST/MONO...................
C
 1003   IF ((GEOM.EQ.1.0).AND.(FLUX.EQ.1.0)) THEN
C
                PP = 1.0 - FTD/100.0
C
                SUMVOL = 0.0
                SUM    = 0.0
                PT     = 0
                I      = (RFO - RFI)/Q
C
                DO 27 RAD = RFI,RFO,I
                   PT = PT + 1
                   Z = RAD/RFO
C
        IF (FTYPE.EQ.0.0) THEN
C
                C = (1.0 - PP)/(1.0 + 0.5*PP)
C
                   PART = (0.91111/1.45504)*(TFS**1.45504) +
     +                     100.0*((Q3TAVG/2)*
     +                     (RFI**2.0*ALOG(Z) + RFO**2.0/2.0*
     +                     (1.0 - (RAD/RFO)**2.0)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            0.91111*(T**0.45504) [BEFORE INTEGRATION]
```

```
C             (0.91111/1.45504)*(T**1.45504) [AFTER INTEGRATION]
C
                   TRAD = (PART*1.45504/0.91111)**(1/1.45504)
C
          ELSE
C
               C = (1.0 - PP)/(1.0 + PP)
C
                  PART = (1.74900/1.34123)*(TFS**1.34123) +
     +                    100.0*((Q3TAVG/2)*
     +                    (RFI**2.0*ALOG(Z) + RFO**2.0/2.0*
     +                    (1.0 - (RAD/RFO)**2.0)))/C
C
C
C       THE INTEGRAL OF THE FUEL CONDUCTIVITY EQUATION FROM THE
C        FUEL SUFRACE TO SOME UNKNOWN RADIUS (RAD) IS SHOWN BELOW.
C        THE EQUATION BELOW HAS A NONLINEAR FORM;  REF: J.K. THOMAS,
C        DEPT. OF NUCLEAR ENGINEERING, TEXAS A&M UNIVERSITY.
C
C            1.74900*(T**0.34123) [BEFORE INTEGRATION]
C            (1.74900/1.34123)*(T**1.34123) [AFTER INTEGRATION]
C
                   TRAD = (PART*1.34123/1.74900)**(1/1.34123)
C
        ENDIF
C
                  IF (PT.EQ.1) THEN
                    TRADVOL = TRAD*(RAD + I/2.0)**2.0
                  ENDIF
                  IF ((PT.GT.1).AND.(PT.LT.Q1)) THEN
                    TRADVOL = TRAD*((RAD + I/2.0)**2.0 -
     +                                (RAD - I/2.0)**2.0)
                  ENDIF
                  IF (PT.EQ.Q1) THEN
                    TRADVOL = TRAD*(RAD**2.0 - (RAD - I/2.0)**2.0)
                  ENDIF
C
                  SUMVOL = SUMVOL + TRADVOL
C
                  TRADPT2(PT) = TRAD
C
                  SUM = SUM + TRAD
C
 27            CONTINUE
C
C       THIS TWO LINES ARE USED TO CALCULATE THE AREA AVERAGE FUEL TEMP.
C        AND STRAIGHT AVERAGE FUEL TEMPERATURE FROM THE PREVIOUS LINES.
C
        TFAVGVOL2 = SUMVOL/RFO**2.0
        TFAVG2 = SUM/Q1
C
        DO 2007 KK = 1,Q1,1
                EPSF = ABS(TRADPT2(KK) - TRADPT1(KK))/TRADPT2(KK)
                  IF (EPSF.GT.CONV) THEN
                     CALL GAP (TFS,TFAVGVOL2,TRADPT1,TRADPT2,TGAVG2,
     +                         GAPHOT,CLOSEDGAP)
                     GO TO 1003
                  ENDIF
 2007   CONTINUE
C
        WRITE (6,757)
 757    FORMAT (//,15X,'FUEL TEMPERATURE DISTRIBUTIONS')
C
           DO 37 P = 1,Q1,1
             WRITE (6,47) P, TRADPT2(P)
 47          FORMAT (5X,'FUEL TEMP. AT RADIUS',1X,I2,1X,'> ',F8.2,' K')
 37        CONTINUE
C
        WRITE (6,517) TFAVGVOL2
 517    FORMAT (/,5X,'AVG. VOL. FUEL TEMP. @ PEAK LOCATION  > ',F8.2,' K')
C
        WRITE (6,57) TFAVG2
 57     FORMAT (/,5X,'AVG. FUEL TEMP. @ PEAK AXIAL LOCATION > ',F8.2,' K')
C
C
        GO TO 999
C
        ENDIF
C
C
```

```
 999     CONTINUE
C
C
C       WRITE (6,*) 'ITERF      > ',ITERF
C
        WRITE (6,78) TFS
        WRITE (6,77) TGAVG2
C       WRITE (6,*)  'ITERG     > ',ITERG
C
 78     FORMAT (/,5X,'FUEL SURFACE TEMP.        > ',F8.2,' K')
 77     FORMAT (5X,'GAP AVERAGE TEMP.   > ',F8.2,' K')
C
        WRITE (6,1987) GAPHOT
 1987   FORMAT (/,5X,'"HOT" GAP WIDTH   > ',E15.8,' cm')
C
        IF (CLOSEDGAP.EQ.1.0) THEN
C
          WRITE (6,1986)
 1986     FORMAT (5X,'PCI               >  NO ')
C
        ELSE
C
          WRITE (6,1985)
 1985     FORMAT (5X,'PCI               >  YES ')
C
        ENDIF
C
C
        RETURN
        END
C
C
C       ..............................................................
C       ..............................................................
C       ..............................................................
C       ..............................................................
C       ..............................................................
C
C
        REAL FUNCTION KUN(ENRICH,FTD)
              IMPLICIT REAL (A-Z)
C
C         BELOW ARE THE CONSTANTS AND ATOMIC WEIGHTS USED IN THE
C          CALCULATION OF THE ATOMIC DENSITY WHICH WILL BE THEN USED
C          TO FIND THE INVERSE OF THE DIFFUSION LENGTH FOR A GIVEN
C          ENRICHMENT.
C
          AVO     = 6.022E23
          U235    = 235.04394
          U238    = 238.05082
          UNAT    = 238.07000
          N14     = 14.0080
C
C         THE DENSITY OF THE FUEL IS COMPUTED BY DENSITY(100%)*(%TD)
C          FUEL DENSITY IN UNITS OF G/CM**3
C
          DENSUN = (14.32)*(FTD/100.0)
C
C         BELOW ARE THE NECESSARY CROSS SECTIONS OF THE UN FUEL
C
          CAPU235  = 101.0E-24
          CAPU238  = 2.730E-24
          FISU235  = 577.0E-24
          SCATUNAT = 8.300E-24
          SCATN14  = 10.00E-24
          ABSN14   = 1.880E-24
C
C         THIS SECTION FINDS THE NUMBER DENSITY (ND) OF UN AND
C          FROM THIS THE INDIVIDUAL NUMBER DENSITIES OF THE
C          CONSTITUENTS.
C
          NDUN = (DENSUN*AVO)/(U235*ENRICH/100.0 +
     +           (1.0 - ENRICH/100.0)*U238 + N14)
C
          NDUNAT = NDUN
          NDN14  = NDUN
          NDU235 = NDUN*ENRICH/100.0
          NDU238 = NDUN*(1.0 - ENRICH/100.0)
C
C         NOW FIND THE MACRO-ABSORPTION CROSS SECTION OF THE FUEL
```

```
C                     ABSORPTION = CAPTURE + FISSION
C
      EAF = NDN14*ABSN14 + NDU235*(CAPU235 + FISU235) +
     +      NDU238*CAPU238
C
C     NOW FIND THE MACRO-TRANSPORT CROSS SECTION OF THE FUEL
C           TRANSPORT = SUMMATION OF SCATTER*(1-2/(3A))
C
      ETRF = NDN14*SCATN14*(1.0 - 2.0/(3.0*N14)) +
     +       NDUNAT*SCATUNAT*(1.0 - 2.0/(3.0*UNAT))
C
C     NOW FIND THE SQUARE OF THE DIFFUSION LENGHT. PROCEED TO TAKE
C      SQUARE ROOT AND THEN FIND THE INVERSE.
C
      X   = 1.0/(3.0*ETRF*EAF)
      L   = SQRT(X)
      KUN = 1.0/L
C
      RETURN
      END
C
C
C
      REAL FUNCTION KUPUN(ENRICH,FTD)
            IMPLICIT REAL (A-Z)
C
C       BELOW ARE THE CONSTANTS AND ATOMIC WEIGHTS USED IN THE
C        CALCULATION OF THE ATOMIC DENSITY WHICH WILL BE THEN USED
C        TO FIND THE INVERSE OF THE DIFFUSION LENGTH FOR A GIVEN
C        ENRICHMENT.
C
      AVO    = 6.022E23
      U235   = 235.04394
      U238   = 238.05082
      UNAT   = 238.07000
      PU239  = 239.05218
      N14    = 14.0080
C
C     THE DENSITY OF THE FUEL IS COMPUTED BY DENSITY(100%)*(%TD)
C      FUEL DENSITY IN UNITS OF G/CM**3
C
      DENSUN = (14.18)*(FTD/100.0)
C
C     BELOW ARE THE NECESSARY CROSS SECTIONS OF THE UN FUEL
C
      CAPU235  = 101.0E-24
      CAPU238  = 2.730E-24
      FISU235  = 577.0E-24
      SCATUNAT = 8.300E-24
      FISPU239 = 741.0E-24
      ABSPU239 = 1015.E-24
      SCATPU239= 9.600E-24
      SCATN14  = 10.00E-24
      ABSN14   = 1.880E-24
C
C     THIS SECTION FINDS THE NUMBER DENSITY (ND) OF UN AND
C      FROM THIS THE INDIVIDUAL NUMBER DENSITIES OF THE
C      CONSTITUENTS.
C
      NDUN = (DENSUN*AVO)/((U235*ENRICH/100.0 +
     +       (1.0 - ENRICH/100.0)*U238)*0.8 + 0.2*PU239 + N14)
C
      NDUNAT  = NDUN
      NDN14   = NDUN
      NDU235  = NDUN*0.8*ENRICH/100.0
      NDU238  = NDUN*0.8*(1.0 - ENRICH/100.0)
      NDPU239 = NDUN*0.2
C
C     NOW FIND THE MACRO-ABSORPTION CROSS SECTION OF THE FUEL
C                 ABSORPTION = CAPTURE + FISSION
C
      EAF = NDN14*ABSN14 + NDU235*(CAPU235 + FISU235) +
     +      NDU238*CAPU238 + NDPU239*ABSPU239
C
C     NOW FIND THE MACRO-TRANSPORT CROSS SECTION OF THE FUEL
C           TRANSPORT = SUMMATION OF SCATTER*(1-2/(3A))
C
      ETRF = NDN14*SCATN14*(1.0 - 2.0/(3.0*N14)) +
     +       NDUNAT*SCATUNAT*(1.0 - 2.0/(3.0*UNAT)) +
     +       NDPU239*SCATPU239*(1.0 - 2.0/(3.0*PU239))
```

```
C
C         NOW FIND THE SQUARE OF THE DIFFUSION LENGHT. PROCEED TO TAKE
C          SQUARE ROOT AND THEN FIND THE INVERSE.
C
          X   = 1.0/(3.0*ETRF*EAF)
          L   = SQRT(X)
          KUPUN = 1.0/L
C
        RETURN
        END
C
C
C
C       ********************
C       THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY OF THE FUEL
C        AT THE FUEL OUTER FUEL SURFACE AND USES THIS NUMBER FOR THE
C        TEMPERATURE DROP ACROSS THE GAP WITH THE GAP FORMULATIONS.
C
        REAL FUNCTION KFGAP(FTYPE,TFS,FTD)
                IMPLICIT REAL (A-Z)
C
C       MATERIAL: UN (MONONITRIDE 400<T<2100 K) REF: ANL-AFP-27
C        *TEMPERATURE MUST BE IN DEGREES KELVIN (K)
C
          IF (FTYPE.EQ.0.0) THEN
            CC = (1.0 - (1.0 - FTD/100.0))/(1.0 + 0.5*(1.0 - FTD/100.0))
C
            KFGAP = CC*(4.63 + 2.32E-2*TFS - 5.96E-6*TFS**2.0)/100.0
          ENDIF
C
C       MATERIAL: UPUN (MIXNITRIDE 400<T<1900 K) REF: ANL-AFP-27
C        *TEMPERATURE MUST BE IN DEGREES KELVIN (K)
C
          IF (FTYPE.EQ.1.0) THEN
            CC = (1.0 - (1.0 - FTD/100.0))/(1.0 + (1.0 - FTD/100.0))
C
            KFGAP = CC*(10.297 + 9.538E-3*TFS - 1.484E-6*TFS**2.0)/100.0
          ENDIF
C
        RETURN
        END
C
C
C
C       ********************
C       THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY (W/CM-K)
C        FOR A PARTICULAR CLADDING AND AVERAGE CLAD TEMPERATURE.
C
        REAL FUNCTION KC(CLTYPE,TEMP)
                IMPLICIT REAL (A-Z)
C
C         MATERIAL:  NIOBIUM (Nb-1%Zr)     REF: FUNDAMENTALS OF HEAT &
C          MASS TRANSFER BY INCROPERA AND DEWITT, P. 757.
C
          IF (CLTYPE.EQ.0.0) THEN
                KC = 0.000147222*TEMP + 0.496
          ENDIF
C
C         MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: FUNDAMENTALS OF
C          HEAT & MASS TRANSFER BY INCROPERA AND DEWITT, P. 758.
C
          IF (CLTYPE.EQ.1.0) THEN
                KC = 0.00004*TEMP + 0.562
          ENDIF
C
C         MATERIAL:  SS-316 & 316L         REF: FUNDAMENTALS OF HEAT &
C          MASS TRANSFER BY INCROPERA AND DEWITT, P. 757.
C
          IF (CLTYPE.EQ.2.0) THEN
                KC = 0.000150*TEMP + 0.0925
          ENDIF
C
C         MATERIAL:  SS-304                REF: FUNDAMENTALS OF HEAT &
C          MASS TRANSFER BY INCROPERA AND DEWITT, P. 757.
C
          IF (CLTYPE.EQ.3.0) THEN
                KC = 0.000140*TEMP + 0.114
          ENDIF
C
C         MATERIAL:  W - 26% Re            REF: REFRACTORY METALS IN
```

```
C          SPACE NUCLEAR POWER BY LYNN B. LUNDBERG, P. 45. (NOTE:
C          THERMAL CONDUCTIVITY IN UNITS OF W/CM-K @ 1500 K)
C
           IF (CLTYPE.EQ.4.0) THEN
                KC = 0.60
           ENDIF
C
         RETURN
         END
C
C
C
C        ********************
C        THIS FUNCTION COMPUTES THE THERMAL CONDUCTIVITY (W/CM-K) OF THE
C         LINER CORRESPONDING TO A PARTICULAR LINER COMPOSITION AND TEMP.
C
         REAL FUNCTION KL(LITYPE,TEMP)
                 IMPLICIT REAL (A-Z)
C
C        MATERIAL: TUNGSTEN  REF: FUNDAMENTALS OF HEAT & MASS TRANSFER
C         BY INCROPERA AND DEWITT, P. 758.
C
               IF (LITYPE.EQ.0.0) THEN
C
                 IF (TEMP.LE.600.0) THEN
                         KL = -0.001225*TEMP + 2.097
                 ENDIF
C
                 IF ((TEMP.GT.600.0).AND.(TEMP.LE.1000.0)) THEN
                         KL = -0.000475*TEMP + 1.647
                 ENDIF
C
                 IF (TEMP.GT.1000.0) THEN
                         KL = -0.00018*TEMP + 1.348
                 ENDIF
C
               ENDIF
C
         RETURN
C
         END
C
C
C
C        ********************
C        THIS FUNCITON COMPUTES THE THERMAL EXPANSION COEFF. FOR
C         A PARTICULAR CLAD TYPE FOR AN AVERAGE CLAD TEMPERATURE.
C
         REAL FUNCTION EXPC(CLTYPE,TCAVG)
                 IMPLICIT REAL (A-Z)
C
C          MATERIAL:  NIOBIUM (Nb-1%Zr)    REF: MECHANICAL AND PHYSICAL
C           PROPERTIES OF REFRACTORY METALS AND ALLOYS BY J.B. CONWAY,
C           P. 231. (25<T<2500 C) NOTE: THESE EXP. COEFFS. WERE MODIFIED
C           BECAUSE THEY WERE REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C           *TEMPERATURES MUST BE IN UNITS OF CELCIUS (C)
C
           IF (CLTYPE.EQ.0.0) THEN
                 TCAVGC = TCAVG - 273.2
                 EXPC = (-4.10E-5 + 5.96E-6*TCAVGC + 1.34E-9*(TCAVGC**2.0))/
     +                  (TCAVGC - 25.0)
           ENDIF
C
C          MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: MECHANICAL AND
C           PHYSICAL PROPERTIES OF REFRACTORY METALS AND ALLOYS BY J.B. CONWAY,
C           P. 231. (25<T<2500 C) NOTE: THESE EXP. COEFFS. WERE MODIFIED
C           BECAUSE THEY WERE REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C           *TEMPERATURES MUST BE IN UNITS OF CELCIUS (C)
C
           IF (CLTYPE.EQ.1.0) THEN
                 TCAVGC = TCAVG - 273.2
                 EXPC = (-7.34E-5 + 5.36E-6*TCAVGC + 1.26E-9*(TCAVGC**2.0))/
     +                  (TCAVG - 25.0)
           ENDIF
C
C          MATERIAL:  SS-316 & 316L        REF:  SOURCE BOOK OF INDUSTRIAL
C           ALLOY AND ENGINEERING DATA, AMERICAN SOCIETY FOR METALS,
C           1978, P. 207.
C
           IF (CLTYPE.EQ.2.0) THEN
```

```
C
            IF (TCAVGC.LE.588.6) THEN
               EXPC = 8.3488E-10*TCAVG + 1.5709E-5
            ENDIF
C
            IF ((TCAVGC.GT.588.6).AND.(TCAVGC.LE.810.8)) THEN
               EXPC = 5.6706E-9*TCAVG + 1.28623E-5
            ENDIF
C
            IF (TCAVGC.GT.810.8) THEN
               EXPC = 9.0713E-9*TCAVG + 1.0105E-5
            ENDIF
C
         ENDIF
C
C        MATERIAL:  SS-304              REF:  SOURCE BOOK OF INDUSTRIAL
C         ALLOY AND ENGINEERING DATA, AMERICAN SOCIETY FOR METALS,
C         1978, P. 206.
C
         IF (CLTYPE.EQ.3.0) THEN
               EXPC = 2.6234E-9*TCAVG + 1.6277E-5
         ENDIF
C
C        MATERIAL:  W - 26% Re          REF: MECHANICAL AND PHYSICAL
C         PROPERTIES OF REFRACTORY METALS AND ALLOYS BY J.B. CONWAY,
C         P. 231. (25<T<2500 C) NOTE: THESE EXP. COEFFS. WERE MODIFIED
C         BECAUSE THEY WERE REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C         *TEMPERATURES MUST BE IN UNITS OF CELCIUS (C)
C
         IF (CLTYPE.EQ.4.0) THEN
               TCAVGC = TCAVG - 273.2
               EXPC = (-8.46E-6 + 3.91E-6*TCAVGC + 1.14E-9*(TCAVGC**2.0))/
     +                (TCAVGC - 25.0)
         ENDIF
C
      RETURN
      END
C
C
C
C     ********************
C     THIS FUNCTION COMPUTES THE THERMAL EXPANSION COEFF. FOR
C      A PARTICULAR FUEL AND AVERAGE FUEL TEMPERATURE.
C
      REAL FUNCTION EXPF(FTYPE,TFAVG1)
            IMPLICIT REAL (A-Z)
C
C       MATERIAL: UN (MONONITRIDE 293<T<1873 K)   REF:  ANL-AFP-27
C        NOTE: THESE EXP. COEFF. WERE MODIFIED BECAUSE THEY WERE
C        REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C        *TEMPERATURES MUST BE IN UNITS OF KELVIN (K)
C
         IF (FTYPE.EQ.0.0) THEN
               EXPF = (-2.49E-3 + 7.80E-6*TFAVG1 + 1.11E-9*(TFAVG1**2.0))/
     +                (TFAVG1 - 298.2)
         ENDIF
C
C        MATERIAL: UPUN (MIXNITRIDE 298<T<1800 K)  REF:  ANL-AFP-27
C         NOTE: THESE EXP. COEFF. WERE MODIFIED BECAUSE THEY WERE
C         REFERENCED AS (EXP. COEFF. x TEMP. DROP)
C         *TEMPERATURES MUST BE IN UNITS OF KELVIN (K)
C
         IF (FTYPE.EQ.1.0) THEN
               EXPF = (-2.26E-3 + 6.95E-6*TFAVG1 + 1.63E-9*(TFAVG1**2.0))/
     +                (TFAVG1 - 298.2)
         ENDIF
C
      RETURN
      END
C
C
C
C     ********************
C     THIS FUNCTION CALCULATES THE MEYER HARDNESS NUMBER FOR
C      VARIOUS TYPES OF CLADDING (NOTE: FOR THIS PROGRAM THE
C      MEYER'S HARDNESS NUMBER WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF CLADDING AND TREATED AS IF ONLY
C      THE MATERIAL ZIRCALOY WAS USED. REF: NUCLEAR POWER PLANT
C      ENGINEERING BY J.H. RUST, P. 298.
C      *MEYER HARDNESS NUMBERS MUST HAVE UNITS OF PSI (lbs/cm**2)
```

```
C
      REAL FUNCTION MEYERC(CLTYPE)
            IMPLICIT REAL (A-Z)
C
C       MATERIAL:  NIOBIUM (Nb-1%Zr)     REF: SEE ABOVE
C
        IF (CLTYPE.EQ.0.0) THEN
            MEYERC = 14.2E4
        ENDIF
C
C       MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: SEE ABOVE
C
        IF (CLTYPE.EQ.1.0) THEN
            MEYERC = 14.2E4
        ENDIF
C
C       MATERIAL:  SS-316 & 316L         REF: SEE ABOVE
C
        IF (CLTYPE.EQ.2.0) THEN
            MEYERC = 13.0E4
        ENDIF
C
C       MATERIAL:  SS-304                REF: SEE ABOVE
C
        IF (CLTYPE.EQ.3.0) THEN
            MEYERC = 13.0E4
        ENDIF
C
C       MATERIAL:  W - 26% Re            REF: SEE ABOVE
C
        IF (CLTYPE.EQ.4.0) THEN
            MEYERC = 14.2E4
        ENDIF
C
C
      RETURN
      END
C
C
C
C     ********************
C     THIS FUNCTION CALCULATES THE MEYER HARDNESS NUMBER FOR
C      VARIOUS TYPES OF LINERS (NOTE: FOR THIS PROGRAM THE
C      MEYER'S HARDNESS NUMBER WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF LINERS AND TREATED AS IF ONLY
C      THE MATERIAL ZIRCALOY WAS USED. REF: NUCLEAR POWER PLANT
C      ENGINEERING BY J.H. RUST, P. 298.
C      *MEYER HARDNESS NUMBERS MUST HAVE UNITS OF PSI (lbs/cm**2)
C
      REAL FUNCTION MEYERL(LITYPE)
            IMPLICIT REAL (A-Z)
C
C       MATERIAL: TUNGSTEN  REF: SEE ABOVE
C
        IF (LITYPE.EQ.0.0) THEN
            MEYERL = 14.2E4
        ENDIF
C
      RETURN
C
      END
C
C
C
C     ********************
C     THIS FUNCTION CALCULATES THE SURFACE ROUGHNESS  FOR
C      VARIOUS TYPES OF CLADDING (NOTE: FOR THIS PROGRAM THE
C      SURFACE ROUGHNESS  WILL BE HELD CONSTANT FOR ALL
C      THE DIFFERENT TYPES OF CLADDING AND TREATED AS IF ONLY
C      THE MATERIAL ZIRCALOY WAS USED. REF: NUCLEAR POWER
C      PLANT ENGINEERING BY J.H. RUST, P. 138.
C
      REAL FUNCTION R1(CLTYPE)
            IMPLICIT REAL (A-Z)
C
C       MATERIAL:  NIOBIUM (Nb-1%Zr)     REF: SEE ABOVE
C
        IF (CLTYPE.EQ.0.0) THEN
            R1 = 0.0001524
        ENDIF
```

```
C
C         MATERIAL:  TANTALUM (T-111/Ta-8%W-2%Hf)  REF: SEE ABOVE
C
          IF (CLTYPE.EQ.1.0) THEN
                R1 = 0.0001524
          ENDIF
C
C         MATERIAL:  SS-316 & 316L         REF: SEE ABOVE
C
          IF (CLTYPE.EQ.2.0) THEN
                R1 = 0.0001524
          ENDIF
C
C         MATERIAL:  SS-304                REF: SEE ABOVE
C
          IF (CLTYPE.EQ.3.0) THEN
                R1 = 0.0001524
          ENDIF
C
C         MATERIAL:  W - 26% Re            REF: SEE ABOVE
C
          IF (CLTYPE.EQ.4.0) THEN
                R1 = 0.0001524
          ENDIF
C
        RETURN
        END
C
C
C
C       **********************
C       THIS FUNCTION CALCULATES THE SURFACE ROUGHNESS  FOR
C        VARIOUS TYPES OF FUEL COMPOSITIONS (NOTE: FOR THIS PROGRAM
C        THE SURFACE ROUGHNESS  WILL BE HELD CONSTANT FOR ALL
C        THE DIFFERENT TYPES OF COMPOSITION AND TREATED AS IF ONLY
C        THE FUEL MATERIAL WAS ZIRCALOY. REF: NUCLEAR POWER PLANT
C        ENGINEERING BY J.H. RUST, P. 138.
C
        REAL FUNCTION R2(FTYPE)
                IMPLICIT REAL (A-Z)
C
C       MATERIAL: UN (MONONITRIDE) REF: SEE ABOVE
C
          IF (FTYPE.EQ.0.0) THEN
                R2 = 0.0001524
          ENDIF
C
C       MATERIAL: UPUN (MIXNITRIDE) REF: SEE ABOVE
C
          IF (FTYPE.EQ.1.0) THEN
                R2 = 0.0001524
          ENDIF
C
        RETURN
        END
C
C
C
C       **********************
C       THIS FUNCTION CALCULATES THE SURFACE ROUGHNESS  FOR
C        VARIOUS TYPES OF LINER COMPOSITIONS (NOTE: FOR THIS PROGRAM
C        THE SURFACE ROUGHNESS  WILL BE HELD CONSTANT FOR ALL
C        THE DIFFERENT TYPES OF COMPOSITION AND TREATED AS IF ONLY
C        THE FUEL MATERIAL WAS ZIRCALOY. REF: NUCLEAR POWER PLANT
C        ENGINEERING BY J.H. RUST, P. 138.
C
        REAL FUNCTION R3(LITYPE)
                IMPLICIT REAL (A-Z)
C
C         MATERIAL: TUNGSTEN  REF: SEE ABOVE
C
          IF (LITYPE.EQ.0.0) THEN
                R3 = 0.0001524
          ENDIF
C
        RETURN
C
        END
        REAL FUNCTION BSIO(V)
                IMPLICIT REAL (A-Z)
```

```
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [I] OF THE FIRST KIND
C          OF ORDER ZERO;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GE.-3.75).AND.(V.LE.3.75)) THEN
              T = V/3.75
              BSIO = 1 + 3.51562*(T**2) + 3.08994*(T**4) +
     +         1.20674*(T**6) + 0.26597*(T**8) +
     +         0.03607*(T**10) + 0.00458*(T**12)
      ELSE
              T = V/3.75
              BSIO = (0.39894 + 0.01328*(T**-1) + 0.00225*(T**-2) -
     +         0.00157*(T**-3) + 0.00916*(T**-4) - 0.02057*(T**-5) +
     +         0.02635*(T**-6) - 0.01647*(T**-7) + 0.00392*(T**-8))/
     +         (SQRT(V)*EXP(-V))
      ENDIF
C
      RETURN
      END
C
C
C
      REAL FUNCTION BSI1(V)
              IMPLICIT REAL (A-Z)
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [I] OF THE FIRST KIND
C          OF ORDER ONE;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GE.-3.75).AND.(V.LE.3.75)) THEN
              T = V/3.75
              BSI1 = (0.5 + 0.87890*(T**2) + 0.51498*(T**4) +
     +         0.15084*(T**6) + 0.02658*(T**8) + 0.00301*(T**10) +
     +         0.00032*(T**12))/(V**-1)
      ELSE
              T = V/3.75
              BSI1 = (0.39894 - 0.03988*(T**-1) - 0.00362*(T**-2) +
     +         0.00163*(T**-3) - 0.01031*(T**-4) + 0.02282*(T**-5) -
     +         0.02895*(T**-6) + 0.01787*(T**-7) - 0.00420*(T**-8))/
     +         (SQRT(V)*EXP(-V))
      ENDIF
C
      RETURN
      END
C
C
      REAL FUNCTION BSKO(V)
              IMPLICIT REAL (A-Z)
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [K]OF THE FIRST KIND
C          OF ORDER ZERO;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GT.0.0).AND.(V.LE.2.0)) THEN
              T = V/2
              BIOR = BSIO(V)
              BSKO = (-ALOG(T)*BIOR) - 0.57721 + 0.42278*(T**2) +
     +         0.23069*(T**4) + 0.03488*(T**6) + 0.00262*(T**8) +
     +         0.00010*(T**10) + 0.00000740*(T**12)
      ELSE
              T = 2/V
              BSKO = (1.25331 - 0.07832*T + 0.02189*(T**2) -
     +         0.01062*(T**3) + 0.00587*(T**4) - 0.00251*(T**5) +
     +         0.00053*(T**6))/(SQRT(V)*EXP(V))
      ENDIF
C
      RETURN
      END
C
C
C
      REAL FUNCTION BSK1(V)
              IMPLICIT REAL (A-Z)
C
C         THIS SUBROUTINE CONTAINS THE POLYNOMIAL APPROXIMATION
C          FOR THE MODIFIED BESSEL FUNCTION [K]OF THE FIRST KIND
```

```
C          OF ORDER ONE;  REF: HANDBOOK OF MATHEMATICAL FUNCTIONS
C          BY ABRAMOWITZ AND STEGUN, P. 378.
C
      IF ((V.GT.0.0).AND.(V.LE.2.0)) THEN
            T = V/2
            BI1R = BSI1(V)
            BSK1 = (V*ALOG(T)*BI1R + 1.0 + 0.15443*(T**2) -
     +           0.67278*(T**4) - 0.18156*(T**6) - 0.01919*(T**8) -
     +           0.00110*(T**10) - 0.00004*(T**12))/V
      ELSE
            T = 2/V
            BSK1 = (1.25331 + 0.23498*(T) - 0.03655*(T**2) +
     +           0.01504*(T**3) - 0.00780*(T**4) + 0.00325*(T**5) -
     +           0.00068*(T**6))/(SQRT(V)*EXP(V))
      ENDIF
C
      RETURN
      END
```

DOSE_4_NEPTUNE

SHIELDING OPTIMIZATION CODE

```
      PROGRAM DOSE_4_NEPTUNE
*************************************************************
* VARIABLES
*
* FLUXC => TOTAL FLUX OF THE CORE
* FLSI  => TOTAL FLUX ENTERING THE SHIELDING
* FFLXO => FRACTION OF THE TOTAL FLUX EXITING THE SHIELDING
* FLUXP => NEUTRON FLUX REACHING THE PAYLOAD
* R     => DISTANCE FROM THE CENTER OF THE CORE TO THE SHIELDING
* RS    => RADIUS OF THE SHIELDING
* D     => DISTANCE FROM THE SHIELDING TO THE PAYLOAD
* FRAC  => FRACTION OF THE TOTAL FLUX THAT ENTERS THE SHIELDING
* NDOSE => NEUTRON FLUX TO DOSE CONVERSION FACTOR
* GFLX  => FLUX OF GAMMAS EXITING THE LIH SHIELDING
* GFLXW => FLUX OF GAMMAS EXITING THE TUNGSTEN SHIELDING
* GFLXHI=> FLUX OF GAMMAS ENTERING THE HG PROPELLANT
* GFLXHO=> FLUX OF GAMMAS EXITING THE HG PROPELLANT
* GFLXP => FLUX OF GAMMAS REACHING THE PAYLOAD
* MUPB  => ATTENUATION COEFFICIENT OF LEAD (APPROX. HG)
* MUW   => ATTENUATION COEFFICIENT OF TUNGSTEN
* DHGS  => DISTANCE FROM SHIELDING TO HG TANKS
* DHGP  => DISTANCE FROM THE HG TANKS TO THE PAYLOAD
* TW    => TUNGSTEN SHIELD THICKNESS
* THG   => LENGTH OF THE HG TANKS
* MHG   => MASS OF MERCURY
* MLIH  => MASS OF LIH
* MW    => MASS OF TUNGSTEN
* CL    => CORE LENGTH
* DSS   => DISTANCE FROM SHIELDING TO SECONDARY SYSTEM
* DCS   => DISTANCE FROM CORE TO SHIELDING
* SH    => HEIGHT OF THE SECONDARY SYSTEM
* VLIH  => VOLUME OF THE LIH SHIELDING
* VW    => VOLUME OF THE TUNGSTEN SHIELDING
* RW1   => FIRST RADIUS OF THE TUNGSTEN SHIELDING
* RW2   => SECOND RADIUS OF THE TUNGSTEN SHIELDING
* RLIH1 => FIRST RADIUS OF THE LIH SHIELDING
* RLIH2 => SECOND RADIUS OF THE LIH SHIELDING
* DOSE  => STANDARD MAN DOSE AT PAYLOAD
*************************************************************
      IMPLICIT REAL(A-Z)
      OPEN(1,FILE='DOSE.INP',STATUS='OLD')
      OPEN(2,FILE='DOSE.OUT',STATUS='NEW')
*************************************************************
* READ IN INPUT FROM FILE DOSE.INP
*************************************************************
      READ(1,1)FLUXC,FFLXO,FGFLX,D,TS,TW,DHGS,CL,DCS,DSS,SH,MHG
      WRITE(*,*)FLUXC,FFLXO,FGFLX,D,TS,TW,DHGS,CL,DCS,DSS,SH,MHG
1     FORMAT(//,E12.7,E10.6,2(F10.3)///4(F10.3)///4(F10.3))
*************************************************************
* CONSTANTS
*************************************************************
        PI = 4.0*ATAN(1.0)
      SPYR = 3.15E+7
      NDOSE = 2.8E-11
*************************************************************
* EVALUATE THE FIRST SHIELDING RADII
*************************************************************
        ANGLE = ATAN((SH/2-CL/2)/(CL+DCS+TW+TS+DSS))
        RW1 = ((CL+DCS)*TAN(ANGLE)+CL/2)
        RS = RW1
        RW2 = ((CL+DCS+TW)*TAN(ANGLE)+CL/2)
        RLIH1 = RW2
        RLIH2 = ((CL+DCS+TW+TS)*TAN(ANGLE)+CL/2)
*************************************************************
* EVALUATE THE NEUTRON DOSE
*************************************************************
```

```
      FRAC = (PI*RS**2)/(4*PI*(CL/2+DCS)**2)
      FLXSI = FRAC*FLUXC
      FLXO = FFLXO*FLXSI
      FLUXP = FLXO*100**2/D**2
      DNEUT = NDOSE*FLUXP*SPYR
C*****************************************************************
C* EVALUATE ATTENUATION THROUGH W   (6MEV GAMMAS)
C*****************************************************************
        ATTENW = EXP(-.0416*19.3*TW)
C*****************************************************************
C* EVALUATE THE ATTENUATION THROUGH PB     (6MEV GAMMAS)
C*****************************************************************
        THG = (MHG*1000/13.54)/(PI*RS**2)
        ATTENPB = EXP(-0.0435*11.4*THG)
C*****************************************************************
C*EVALUATE THE DOSE DUE TO GAMMAS
C*****************************************************************
      DHGP = D-DHGS-THG
      GFLX = FGFLX*FLXSI
      GFLXW = GFLX*ATTENW
      GFLXHI = GFLXW*100**2/DHGS**2
      GFLXHO = GFLXHI*ATTENPB
      GFLXP = GFLXHO*100**2/DHGP**2
      DGAMM = GFLXP*6*1.6E-13*0.0178*1000/.01
C*****************************************************************
C* TOTAL DOSE
C*****************************************************************
      DOSE = DNEUT + DGAMM
C*****************************************************************
C* DETERMINE VOLUMES AND MASSES OF THE LIH AND W SHIELDS
C*****************************************************************
      VLIH = PI/3*TS*(RLIH1**2+RLIH2**2+RLIH1*RLIH2)
      VW   = PI/3*TW*(RW1**2+RW2**2+RW1*RW2)
      MLIH = VLIH * .4742/1000
      MW = VW * 19.3/1000
C*****************************************************************
C* OUTPUT
C*****************************************************************
      WRITE(2,2) TS,RS,RW1,RW2,RLIH2,D,DHGS,DHGP,TW,THG,ATTENW,
     &ATTENPB,MHG,MLIH,MW,DNEUT,DGAMM,DOSE
2     FORMAT(2X,'LiH shielding thickness is ',F10.3,' cm'/2x,
     &'shielding radius is ', F10.3,' cm'/2X,
     &'1st radius is ',F10.3,' cm'/2x,
     &'2nd radius is ',F10.3,' cm'/2x,
     &'3rd radius is ',F10.3,' cm'/2x,
     &'distance from LiH to payload is ',F10.3,' cm'/2x,
     &'distance from tungsten to mercury tanks is ',F10.3,' cm'/2x,
     &'distance from mercury tanks to payload is ',F10.3,' cm'/2x,
     &'tungsten shielding thickness is ',F10.3,' cm'/2x,
     &'length of the mercury tanks is ',F10.3,' cm'/2x,
     &'attenuation of W is ',F10.4/2x,
     &'attenuation of Pb is ',F10.4/2x,
     &'mass of HG is ',F10.1,' kg'/2x,
     &'mass of LiH is ',F10.1,' kg'/2x,
     &'mass of W is ',F10.1,' kg'/2x,
     &'dose due to neutrons is ',F10.6,' rem/yr'/2x,
     &'dose due to gammas is ',F10.6,' rem/yr'/2x,
     &'TOTAL DOSE  due to neutrons and gammas from the core = '
     &,F10.3,' rem/yr')
      STOP
      END
```

```
LiH shielding thickness is    180.000 cm
shielding radius is    143.019 cm
1st radius is    143.019 cm
2nd radius is    144.340 cm
3rd radius is    212.264 cm
distance from LiH to payload is  50000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  44744.848 cm
tungsten shielding thickness is      3.500 cm
length of the mercury tanks is    255.151 cm
attenuation of W is     0.0602
attenuation of Pb is     0.0000
mass of HG is   222000.0 kg
mass of LiH is     8628.1 kg
mass of W is     4380.9 kg
dose due to neutrons is  17.568489 rem/yr
dose due to gammas is   0.000000 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =     17.568 rem/yr


LiH shielding thickness is    200.000 cm
shielding radius is    139.847 cm
1st radius is    139.847 cm
2nd radius is    141.117 cm
3rd radius is    213.706 cm
distance from LiH to payload is  50000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  44999.758 cm
tungsten shielding thickness is      3.500 cm
length of the mercury tanks is      0.240 cm
attenuation of W is     0.0602
attenuation of Pb is     0.8876
mass of HG is      200.0 kg
mass of LiH is     9508.7 kg
mass of W is     4188.1 kg
dose due to neutrons is   6.514000 rem/yr
dose due to gammas is   0.000005 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =      6.514 rem/yr


LiH shielding thickness is    220.000 cm
shielding radius is    136.980 cm
1st radius is    136.980 cm
2nd radius is    138.029 cm
3rd radius is    215.009 cm
distance from LiH to payload is  50000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  44999.750 cm
tungsten shielding thickness is      3.000 cm
length of the mercury tanks is      0.251 cm
attenuation of W is     0.0899
attenuation of Pb is     0.8831
mass of HG is      200.0 kg
mass of LiH is    10374.0 kg
mass of W is     3439.3 kg
dose due to neutrons is   2.438332 rem/yr
dose due to gammas is   0.000006 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =      2.438 rem/yr
```

```
LiH shielding thickness is    180.000 cm
shielding radius is    143.019 cm
1st radius is    143.019 cm
2nd radius is    144.340 cm
3rd radius is    212.264 cm
distance from LiH to payload is  55000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  49744.848 cm
tungsten shielding thickness is      3.500 cm
length of the mercury tanks is    255.151 cm
attenuation of W is     0.0602
attenuation of Pb is     0.0000
mass of HG is   222000.0 kg
mass of LiH is     8628.1 kg
mass of W is     4380.9 kg
dose due to neutrons is  14.519414 rem/yr
dose due to gammas is   0.000000 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =     14.519 rem/yr


LiH shielding thickness is    200.000 cm
shielding radius is    139.847 cm
1st radius is    139.847 cm
2nd radius is    141.117 cm
3rd radius is    213.706 cm
distance from LiH to payload is  55000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  49999.758 cm
tungsten shielding thickness is      3.500 cm
length of the mercury tanks is      0.240 cm
attenuation of W is     0.0602
attenuation of Pb is     0.8876
mass of HG is      200.0 kg
mass of LiH is     9508.7 kg
mass of W is     4188.1 kg
dose due to neutrons is   5.383471 rem/yr
dose due to gammas is   0.000004 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =      5.383 rem/yr

LiH shielding thickness is    220.000 cm
shielding radius is    136.980 cm
1st radius is    136.980 cm
2nd radius is    138.029 cm
3rd radius is    215.009 cm
distance from LiH to payload is  55000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  49999.750 cm
tungsten shielding thickness is      3.000 cm
length of the mercury tanks is      0.251 cm
attenuation of W is     0.0899
attenuation of Pb is     0.8831
mass of HG is      200.0 kg
mass of LiH is    10374.0 kg
mass of W is     3439.3 kg
dose due to neutrons is   2.015150 rem/yr
dose due to gammas is   0.000005 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =      2.015 rem/yr
```

```
LiH shielding thickness is    180.000 cm
shielding radius is    143.019 cm
1st radius is    143.019 cm
2nd radius is    144.340 cm
3rd radius is    212.264 cm
distance from LiH to payload is  60000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  54744.848 cm
tungsten shielding thickness is      3.500 cm
length of the mercury tanks is    255.151 cm
attenuation of W is     0.0602
attenuation of Pb is     0.0000
mass of HG is   222000.0 kg
mass of LiH is     8628.1 kg
mass of W is     4380.9 kg
dose due to neutrons is  12.200340 rem/yr
dose due to gammas is   0.000000 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =     12.200 rem/yr


LiH shielding thickness is    200.000 cm
shielding radius is    139.847 cm
1st radius is    139.847 cm
2nd radius is    141.117 cm
3rd radius is    213.706 cm
distance from LiH to payload is  60000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  54999.758 cm
tungsten shielding thickness is      3.500 cm
length of the mercury tanks is      0.240 cm
attenuation of W is     0.0602
attenuation of Pb is     0.8876
mass of HG is      200.0 kg
mass of LiH is     9508.7 kg
mass of W is     4188.1 kg
dose due to neutrons is   4.523611 rem/yr
dose due to gammas is   0.000003 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =      4.524 rem/yr


LiH shielding thickness is    220.000 cm
shielding radius is    136.909 cm
1st radius is    136.909 cm
2nd radius is    138.132 cm
3rd radius is    215.041 cm
distance from LiH to payload is  60000.000 cm
distance from tungsten to mercury tanks is   5000.000 cm
distance from mercury tanks to payload is  54999.750 cm
tungsten shielding thickness is      3.500 cm
length of the mercury tanks is      0.251 cm
attenuation of W is     0.0602
attenuation of Pb is     0.8830
mass of HG is      200.0 kg
mass of LiH is    10381.6 kg
mass of W is     4013.4 kg
dose due to neutrons is   1.691536 rem/yr
dose due to gammas is   0.000003 rem/yr
TOTAL DOSE  due to neutrons and gammas from the core =      1.692 rem/yr
```